EXPERT SYSTEM FOR THE THERMAL DESIGN OF SHELL AND TUBE VERTICAL CONDENSERS

by

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To

My Parents and Sister

CERTIFICATE

This is to certify that the work entitled 'EXPERT SYSTEM FOR THE THERMAL DESIGN OF SHELL AND TUBE VERTICAL CONDENSERS' has been carried out by Mr. SANJAY AGRAWAL under our supervision and has not been submitted elsewhere for the award of a degree.

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Sanjay Agrawal

-Sanjay Agrawal

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ABSTRACT

An Expert System based on Logic Programming for thermal design of Shell and Tube Vertical Condensers having single shell pass and single tube pass has been developed. The present system makes use of Expert System Shell 'VIDHI' based on backward chaining.

The design process of vertical condensers has been transformed into a knowledge base comprising of rules, facts, questions and explanations. The modified 'Bell-Delaware Method' has been used for the shell-side analysis and 'Kern's Method' for the tube-side analysis. The shell-side analysis considers the non-ideal cross flow as it occurs in a shell and tube heat exchanger and the suitable correction factors for the same are calculated to take into account the deviation from the ideal cross flow. For the subcooling and the desuperheating zones, average heat transfer coefficients have been used, while for the condensation zone Stepwise Method has been used, which takes into account the variation in heat transfer coefficient due to compositional change.

NOMENCLATURE

A, A_{tot}	-Total heat transfer area, Eq. (4.45) and Eq. (4.11), m^2
A_o	-Approximate heat transfer area, Eq. (4.3), m^2
A_{con}, A_{desup}, A_{sub}	-Areas for condensation, desuperheating and subcooling zones, m^2
A^*	-Tube-layout density parameter, mm^{-1}
a	-A constant, Eq. (4.21)
b	-A constant, Eq. (4.21)
C_1	- Tube field layout constant, Eq. (4.6)
c_{pl}, c_{pg}	-Specific heat of liquid and vapour phase of condensing fluid, $J.kg^{-1}K^{-1}$
c_{ps}, c_{pt}	-Specific-heat of shell side and tube side fluids, $J.kg^{-1}K^{-1}$
D_{ctl}	-Tube-bundle pitch circle diameter, Eq.(4.5), mm
D_s	-Shell diameter, Eq. (4.4), mm
D_t	-Tube diameter, mm
F	-Flow regime parameter
F_c	-Log mean temperature difference correction factor
f_g	-Gas alone friction factor
G	-A parameter
g_n	-Acceleration due to gravity
h_c	-Condensation heat transfer coefficient, $W.m^{-2}.K^{-1}$
h^+	-Dimensionless heat transfer coefficient
h_i, $h_{si\,deal}$	-Ideal tube bank heat transfer coefficient, $W.m^{-2}.K^{-1}$

h_s, h_t	-Heat transfer coefficient for shell side and tube side flows, $W.m^{-2}.K^{-1}$
h_1	-Condenasation heat transfer coefficient based on gravity dominated flows, $W.m^{-2}.K^{-1}$
h_2	-Condensation heat transfer coefficient based on shear dominated flows, $W.m^{-2}.K^{-1}$
j_b	-Bundle bypass correction factor
j_c	-Segmental baffle window correction factor
j_i, j_h	-j-factors for heat transfer
j_l	-Baffle leakage correction factor
j_r	-Heat transfer correction factor for adverse temperature gradient
k_l , k_g	-Thermal conductivities of liquid and vapour phase, $W.m^{-1}.K^{-1}$
k_s, k_t	-Thermal conductivities of shell side and tube side fluids, $W.m^{-1}.K^{-1}$
L	-Heat transfer length in subcoling zone, m
l	-Tube length, mm
L_{tp}	-Tube pitch, mm
$\dot{m}$	-Total mass flow rate of condensing fluid, $kg.s^{-1}$
$\dot{m}_g$	-Vapour phase mass flow rate, $kg.s^{-1}$
$\dot{m}_s$, $\dot{m}_t$	-Mass velocities of shell side and tube side fluids, $kg.\ m^{-2}.s^{-1}$
$\dot{M}_s$,$\dot{M}_t$	-Mass flow rates of shell side and tube side fluids, $kg.s^{-1}$
N_t	-Total number of tubes
N_{tp}	-Number of tube side passes

Nu	-Nusselt number for condensation
Pr_l	-Prandtl number of condensate
Pr_s , Pr_t	-Prandtl number of shell side and tube side fluids
$\dot{q}$	-Total heat flux, $W.m^{-2}$
$\dot{q}_{con}$	-Heat flux in condensation zone, $W.m^{-2}$
$\dot{q}_{desup}$	-Desuperheating heat flux, $W.m^{-2}$
$\dot{q}_{sub}$	-Subcooling heat flux, $W.m^{-2}$
Re_l	-Condensate Reynolds number
Re_g	-Vapour superficial Reynolds number
Re_s , Re_t	-Reynolds number of shell side and tube side fluids
R_{fs} , R_{ft}	-Fouling factors for heat transfer, Eq. (4.3Ø), $m^2.K.W^{-1}$
r_i, r_o	-Inside and outside radius of tube, mm
S	-Perimeter, mm
S_m	-Cross flow area at shell centreline within one baffle spacing, Eq. (4.7), mm^2
T	-Temperature, Eq. (4.21), K
T_{hi}, T_{ci}	-Inlet temperatures of condensing fluid and coolant, ^oC
T_{ho}, T_{co}	-Outlet temperatures of condensing fluid and coolant, ^oC
$T_{c,i}$	-Inlet temperature of coolant at ith step, ^oC
$T_{c,in}$	-Inlet temperature of coolant at a step, ^oC
$T_{c,out}$	-Outlet temperature of coolant at a step, ^oC
T_{sat}, T_{con}	-Condensing temperature of hot fluid, ^oC
$T_{con,i}$, $T_{con,o}$	-Inlet and outlet temperatures of coolant in

	condensation zone, $^{\circ}C$
T_I	-Interface temperature, $^{\circ}C$
T_W	-Tube wall temperature, $^{\circ}C$
U_o	-Overall heat transfer coefficient, Eq. (4.30), $W.m^{-2}.K^{-1}$
U_i	-Overall heat transfer coefficient for ith step, $W.m^{-2}.K^{-1}$
$U_{subcool}$, U_{desup}	-Overall heat transfer coefficients for subcooling and desuperheating zones, $W.m^{-2}.K^{-1}$
$\dot{V}_g$	-Fictitious vapour velocity, Eq. (3.7), $m.s^{-1}$
y	-Vapour fraction
$y_{inlet\ zone}$	-Vapour fraction at the inlet of condensation zone
$y_{outlet\ zone}$	-Vapour fraction at the outlet of condensation zone

GREEK LETTERS :

ΔA_i	-Area of ith step, m^2
$\Delta \dot{q}_i$	-Heat flux of ith step, $W.m^{-2}$
ΔT_{LM}	-Log mean temperature difference, $^{\circ}C$
$\Delta T_{LM,i}$	-Log mean temperature difference for ith step, $^{\circ}C$
ΔT_{LMds}	-Log mean temperature difference for desuperheating zone, $^{\circ}C$
ΔT_{LMsub}	-Log mean temperature difference for subcooling zones, $^{\circ}C$
δy	-Change in vapour fraction in one step

$\dot{\Gamma}_l$	-Mass flow rate of condensate per unit width, $kg.m^{-1}$
$\dot{\gamma}$	-Function of Reynolds number
η_l, η_g	-Viscosities of liquid and vapour phase of condensing fluid, cP
η_s, η_t	-Viscosities of shell side and tube side fluids at average temperatures, cP
η_l'	-Viscosity of liquid phase of condensing fluid, Pa.s
η_{sw}	-Viscosity of shell side fluid at tube wall temperature, cP
θ	-Taper tube end angle from horizontal, degree
θ_{tp}	-Tube layout angle, degree
τ_I	-Interfacial shear stress, $N.m^{-2}$
τ_I^+	-Dimensionless interfacial shear stress
σ	-Surface tension, N/m
ρ_s ρ_t	-Densities of shell side and tube side fluids, $kg.m^{-3}$
ρ_l ρ_g	-Densities of liquid and vapour phase, $kg.m^{-3}$

ABBREVIATIONS

AI	Artificial Intelligence
LMTD	Log Mean Temperature Difference
STHE	Shell and Tube Heat Exchanger

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LIST OF IMPORTANT PREDICATES

(The list does not include the predicates having only the question rule or fact(s))

1. INTRODUCTION

1.1 Artificial Intelligence And Expert System :

Artificial Intelligence (AI) investigates symbolic, non-algorithmic reasoning processes and the representation of machine inference. AI seeks to transform the way we interact with the computers, enlarge the 'cognitive' abilities of the computers, thereby opening up many new application areas like EXPERT SYSTEMS etc., besides making efforts to provide a computational theory of intelligence.

An expert system is a program containing knowledge from a restricted domain which uses complex inferential reasoning or logical decision making process to carry out tasks normally performed by human experts. An expert system must also be able to:

* engage in a dialogue with a user to acquire the relevant details of the problem
* explain the problem solving process
* get easily modified as new discoveries are made
* deal with partial information. The solutions should degrade gracefully rather than suddenly and completely. (Sangal,1985)

Typical applications of Expert Systems involve interpretation of large amount of data (possibly repetitive) or problems requiring many years of experience and a large store of

unususal facts associated with that experience. Thus, an expert system is based upon encoding the human expert's knowledge. (Engman,1986)

1.2 Structure of the Expert System :

In developing an expert system, the programmer programs the computer on what to do without telling it how to do it. This is a major demarcation from historic computer programming, which is typically a structured set of instructions telling the computer how to process a set of data. Though it has historically provided a powerful and fast analysis tool for specific problems but not a very flexible tool for handling missing data, deductive processes, or poorly defined parameters.

The present expert system is based on the most popular rule-based system or production system. It consists of three major components :

* a knowledge base consisting of if-then rules
* a current context or facts pertaining to the particular problem being solved by the system
* an interpreter deciding the order of application of rules .

1.3 Present Work :

The objective of the present work is to build an expert system for the

* selection of proper type of condenser and
* thermal design of vertical downflow(both shell-side and tube-side condensation) and vertical upflow (tube-side condensation) condensers .

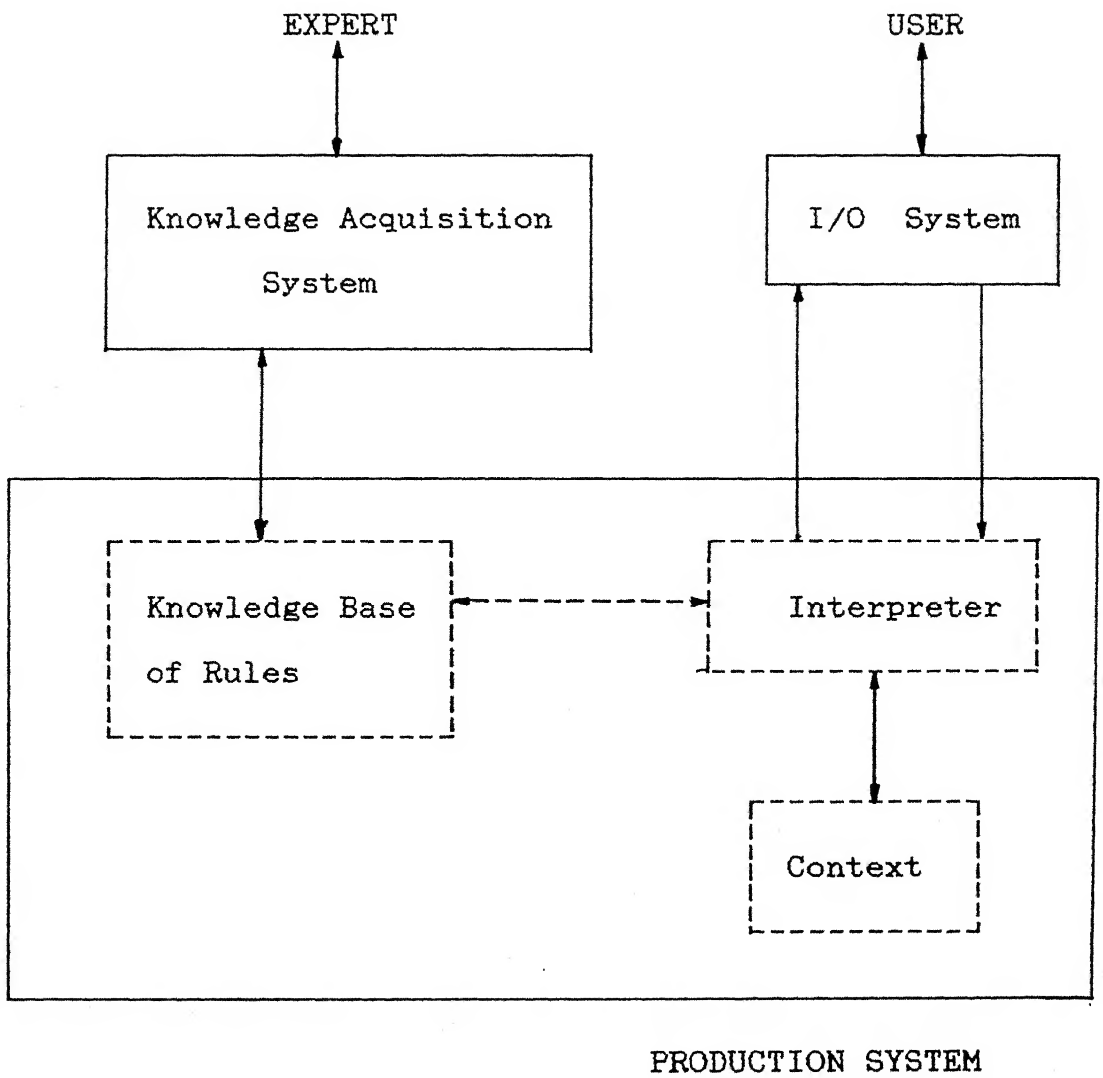


Fig. 1.1 : Structure of an Expert-System

1.4 Motivations Behind the Present Work :

It is seen from literature available on the design of condensers that a very large number of decisions involving logic have to be made in the actual design, e.g. choice of a suitable type of condenser , deciding the type of the bundle, the type of pitch layout etc..Many times certain parameters are already known and so need not be computed and overall design will depend on these known values . The final design is obtained by trial and error until certain criteria are satisfied. There is no unique solution to the design problem, whichever solution suits the needs of the user is ultimately the chosen solution. It is for such ill-structured problems requiring the search in solution space that expert system is most suited.

Thus the important motivations behind the present work are :

(a) to increase the efficiency of an expert

(b) to incorporate additional information in this area .

(c) to provide an aid to expert for confirming his decisions

(d) to act as teaching aid.

1.5 Organisation of the Thesis :

Chapter 2 discusses the Expert System Shell 'VIDHI' which is the basis for the present expert system. Chapters 3 and 4 give all the relevant details for the selection of the type of condensers and the thermal design of vertical condensers. Chapter 5 discusses the structuring of the knowledge base used in the expert system developed. Chapter 6 illustrates the use of the system and some sample sessions have been recorded. Limitations of the system and scope for further work is also outlined.

2. EXPERT SYSTEM SHELL 'VIDHI'

2.1 Introduction :

An expert system shell provides the user with a provision for efficient storage and retrieval of assertions, an appropriate user interface, ability to pose questions to the user (when facts and rules fail) etc., (Sangal,1988). Knowledge related to any particular domain can be entered into it to develop the expert system in that domain.

The shell 'VIDHI' is written in LISP .So while using it one can make use of all the features and facilities of LISP. However, use of VIDHI provides a simpler syntax than that which would be necssary if the program were to be written in LISP.

2.2 Pattern-Matching :

A pattern is an S-expr which might contain zero or more occurrences of wild cards starting with the character '?'. A data item is an S-expr which has no occurrences of wild cards. A pattern matches a data item if on replacing each of the wild cards by an appropriate S-expr, we get the data item.For example, the following two matches:

```
Pattern : (fluid-name hot-fluid ?name-h)
Data-item: (fluid-name hot-fluid steam)
```

because on substituting ?name-h in the pattern by 'steam' we get the data item.

2.3 Logic Programming :

Logic programming discribed here is used for solving problems involving objects and relationships. To express relationships between objects, predicates are used. For example, to express that the pressure of condensing ammonia is high, we make use of two place predicate 'pressure':

(pressure ammonia high)

Here 'pressure' is the predicate and 'ammonia' and 'high' are its arguments.

2.3.1 Terms and Formulas:

Terms occur as arguments of the predicates in formulas and are either variables or constants or function-argument combinations, e.g.

(1) ?x, ?person, ?p3

(2) 3, 5.6, HIGH

(3) a list of the form

(<f> <p1> <p2>....<pn>)

where <f> is a function symbol (a constant) and <p1> to <pn> are arguments (terms), e.g.

(add 2.0 (product 2.0 4.0))

where 'add' is a function followed by its two arguments.

A formula can take one of the following forms:

(1) An atomic formula is a predicate-arguments combination where the predicate is a symbolic atom and the arguments are terms. For example,

(density water 1000.0)

is an atomic formula having 'density' as a predicate and,'water' and '1000.0' as its arguments.

(2) A horn-clause (formula) is of the form

B <- A1.......An   n >= Ø   (2.1)

where B and A1 to An are atomic formulas. B is called the <u>consequent</u> and A1 to An the <u>antecedent</u>. If the antecedent is empty, (n=Ø), horn clause reduces to an atomic formula.

2.3.2 Assertions, Rules, Facts and Query:

Formulas described in the previous section take truth values. Formulas known to be true are known as assertions, e.g.

(greater 3 Ø)

(= 3 (add 2 1))

If a horn-clause of the form given in Eq. (2.1) is included in the data-base, then B is true whenever each member of A1 to An is true. The consequent formula is unconditionally true if the antecedent is empty, e.g.

(cond-type tube-side-condensation) <- (condensing-fluid corrosive)

Here (cond-type tube-side-condensation) is true if (condensing-fluid corrosive) is true.

An assertion with antecedent(s) is called a rule, while an assertion with an empty antecedent is called a fact.

A formula whose truth value is to be determined is called a query or a goal formula. It is written as

goal(cond-type ?1)

If the goal formula has a variable, then the binding of a variable for which the formula true, is the answer.

2.3.3 Inference:

There are two rules of inference using which the truth

value of a formula can be determined to give an initial set of assertions:

a. Universal Instantiation :

Substituting a variable in a rule yields an assertion.

b. Modus Poens (Application of a rule) :

If the formulas in the antecedent of the assertion are true, then the consequent is also true. For example, from the following:

(fluid-name ?x) <- (condensing-fluid ?x)

(condensing-fluid steam)

it can be inferred that

(fluid-name steam)

is true.

2.4 Present Shell 'VIDHI' at the User Level :

VIDHI is based on backward chaining where one begins with the goal and goes backward towards the facts. Computer programming in VIDHI consists of

* declaring some facts about objects and their relationships
* defining some rules about objects and their relationships
* asking questions about objects and their relationships

The way of using the features and characteristics of the 'Shell' are described below in brief:

2.4.1 Facts and Rules:

The syntax for a fact is

(defasrt <fact-name> (<predicate> <arg1><arg2>...<argn>))

and that for a rule is

(defasrt <rule-name> (<predicate><arg1><arg2>...<argn>) <-

```
(<predicate><arg11><arg12>...<arg1n>)
(<predicate><arg21><arg22>...<arg2n>)
.....................................
(<predicate><argm1><argm2>...<argmn>))
```

2.4.2 Posing Questions:

This is a mechanism in the 'Shell' used for eliciting the information from the user. This is accomplished by introducing rules that cause questions to be issued. Such rules make use of a built-in predicate called 'ask-user'.The database is not searched to test the truth value of a formula involving ask-user, instead the interaction takes place with the user. The syntax for 'ask-user' is

```
(ask-user (source <var1> <var2>...<varn>)
          (target <var1> <var2> ...<varm>)
          (question <text of the question>)
          (types <spec1> <spec2>...<specm>))
```

All the source variables should have variable free values, but none of the target variable should have a value.The further details about ask-user can be obtained from VIDHI-Manual.

The results obtained using 'ask-user' are stored automatically.

2.4.3 Storing Intermediate Results:

After a goal or a subgoal has been inferred, it is stored in the data-base if the predicate used in that goal or subgoal has been declared 'intermediate' using the following syntax:

```
(defintermediate <predicate1><predicate2>...<predicate n>).
```

2.4.4 Elaboration :

Text may be associated with a predicate providing a helpful explanation to the user of expert system. It is retrieved gand displayed when user types 'what' in response to a query. The syntax is:

```
(defelaboation <predicate> ( <elaboration/explanation> ))
```

2.4.5 Computational Predicates and Functions :

Computational predicates are 'computed' (i.e., applied to their arguments) to determine the truth value ofa formula in which they occur. All the LISP computational functions and predicates can be used in VIDHI after making the following declarations:

```
(defcompfunc  <VIDHI-name> <LISP name>)
(defcomp <VIDHI-name) <LISP-name>)
```

The use of computational predicates and functions places a restriction on the choice of input and output arguments. All the arguments of a computational function must be known. Moreover, the antecedents become procedural.

2.4.6 Functional Dependencies:

Many times the value of an argument of a predicate can be functionally determined by the value of other arguments. For example, density of water is unique at a given temperature. Thus in

```
(density ?temp ?dens)
```

the ?temp determines ?dens and

```
(density 100.0 958.3)
(density 100.0 1000.0)
```

should not be allowed to be present simultaneously.

This idea is captured using declaration of the type :

(deffd <prdeicate 1> <prdeicate 2>...<predicate n>)

It is assumed in the current implementation that only the first argument is independent and all other arguments are dependent on the first one. The declaration of functional dependency allows inconsistencies to be detected.

2.4.7 'retract-all' Predicate:

Many parameters in any design problem have some fixed value and once this value is determined, the predicates associated with these parameters are no longer needed. In fact there presence may cause problems during backtracking. So the rules involving these predcates are made inapplicable whenever the following built-in-predicate appears in the antecedent of a rule:

(retract-all <predicate>)

2.4.8 Inference Mechanism:

The inference mechanism of the system is similar to that of PROLOG. It doesn't distinguish between rules, facts or question-rules (the rules involving an antecedent having ask-user predicate).

The system accepts any query when the function 'goal' is used, e.g. if the query is (area-req ?1) then

'goal(area-req ?1)'

will try to satisfy the query.

The infer algorithm of the 'Shell' takes the query and does a series of operations :

1. It searches the data-base and checks whether the predicate currently involved is a computational function or predicate and if so, then the arguments are passed onto the compute predicate or function after substituting the values for the arguments of the predicate.

2. If the predicate is one of 'not', 'ask-user', or 'retract-all' then the actions are taken as described in the previous section.

3. If the predicate is not of the type (1) or (2) then the data-base is searched for the rules and facts and stored for it. these are tried in the order in which they appear in the data-base. For facts no new subqueries are generated while for rules a new subquery is generated for every predicate in the antecedent.

The value of arguments of any predicate are stored if the predicate (that gets satisfied used) in that goal or subgoal has been declared 'intermediate'.

3. PRINCIPLES AND CLASSIFICATION OF CONDENSERS

3.1 Modes of Condensation :

Condensation occurs when the temperature of vapour is reduced below its saturation temperature. In industrial equipments, the process commonly results from contact between the vapour and a cool surface and is called 'Surface Condensation'. There are two forms of Surface Condensation (Fig. 3.1) :

(i) Filmwise condensation

(ii) Dropwise condensation .

(i) Filmwise Condensation :

The condensate forms a continuous film on the cooled surface. This is the most important mode of condensation occurring in industrial equipments and is discusssed in detail in this Chapter .

(ii) Dropwise Condensation :

This occurs when the condensate is formed as droplets on a cooled surface instead of a continuous film . High heat transfer coefficients can be obtained with dropwise condensation, but this is difficult to achieve and maintain in heat exchangers.

3.2 Resistances to Condensation :

Figure 3.2 shows the filmwise condensation of pure

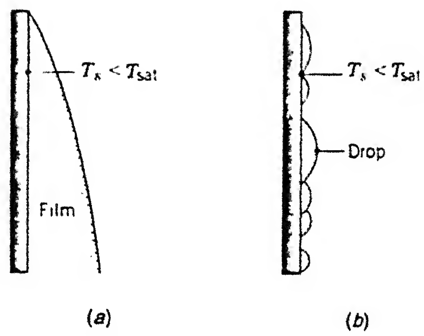


Fig. 3.1 Modes of Condensation

(a) Film Condensation

(b) Dropwise Condensation

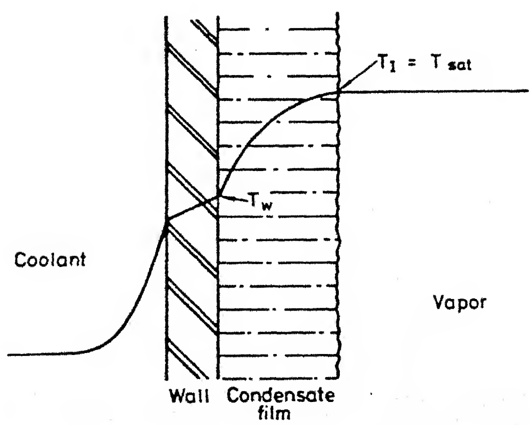


Fig. 3.2 Resistances to Condensation for the Case of a Pure Vapour

vapour which has been assumed as saturated. Temperature drops exist across the condensate film , through the wall and from the wall into the coolant (Butterworth, 1985).

Heat transfer coefficient h_c for the condensate film can be written as

$$h_c = \frac{\dot{q}}{T_I - T_W} = \frac{\dot{q}}{T_{Sat} - T_W} \qquad (3.1)$$

where , $\dot{q}$ = heat flux through the film

T_I = interface temperature

T_{Sat} = saturation temperature of vapour

T_W = wall temperature

In general the following parameters affect the film resistances -

(a) Geometry of surface: (i) Inside of horizontal or vertical tubes
(ii) Outside of horizontal or vertical baffled tube bundles

(b) Vapour hydrodynamics: (i) Condensate film laminar (no vapour shear)
(ii) Gravity induced turbulency
(iii) Vapour shear induced turbulency

(c) Substance: (i) Single component
(ii) Multi-component fully condensable mixtures
(iii) Vapour with noncondensable gas present

The Nusselt number for condensation may be expressed as

$$Nu_c = \frac{h_c \delta}{k_l} \times 10^{-3}$$

where , h_c = heat transfer coefficient for condensation

k_l = thermal conductivity (liquid)

δ = film thickness ; it depends on the force of gravity & vapour shear force

3.3 Condensation Inside or Outside Vertical Tubes :

Value of Nusselt number in this case will depend upon the value of Reynolds number and Prandtl number where ,

$$Re_l = \frac{4\dot{\Gamma}_l}{\eta'_l} \tag{3.2}$$

$$Pr_l = \frac{C_{pl}\eta'_l}{k_l} \tag{3.3}$$

where , $\dot{\Gamma}_l = \frac{\dot{M}}{S} \times 10^3$ condensation drainage length per unit width and

$S = \Pi D$, D being the internal tube diameter for inside tube condensation and outside tube diameter for condensation outside the tubes .

Heat transfer values for both the cases ,viz., shear dominated and gravity dominated flows , should be calculated and maximum of these should be taken as the actual value.

3.3.1 Gravity Dominated Flow:

For Re < 30 , the following relation can be used :

$$h_l = 1.1\ k_l \left[\frac{Re\ \eta'^2_l}{\rho_l(\rho_l - \rho_g)\ g_n}\right]^{-1/3} \tag{3.4}$$

For 30< Re < 1600 , laminar waves start building up and

then ,

$$h_1 = 0.756\ k_1 \left[\frac{\eta'^2_1}{\rho_l (\rho_l - \rho_g) g_n} \right]^{-1/3} (Re_l)^{-0.22} \tag{3.5}$$

For Re > 1600 , turbulence starts having significant effect on heat transfer and then the value of h_1 depends on the Prandtl number also .

For Pr < 10.0 ,

$$h_1 = 0.023\ k_1\ Re_l^{0.25} Pr_l^{0.5} \left[\frac{\eta'^2_1}{\rho_1\ (\rho_1 - \rho_g)\ g_n} \right]^{-1/3} \tag{3.6}$$

For Pr > 10.0 , the above equation can be used with Pr = 10.0.

3.3.2 Shear Dominated Flow:

Henstock and Hanratty (1976)has suggested the following formulation for evaluation of h_2:

$$\dot{V}_g = \frac{\dot{m}_g\ (1-y)}{\rho_g (\Pi D^2/4)} \times 10^6 \tag{3.7}$$

where D is the tube inside diameter for flow inside tubes or the hydraulic mean diameter for downward vapour flow outside the tubes in a bundle.

$$\dot{\gamma} = \left[(0.707\ Re_l^{0.5})^{2.5} + (0.0379\ Re_l^{0.9})^{2.5} \right]^{0.4}$$

$$Re_g = \frac{\rho_g\ V_g\ D}{\eta_g}$$

$$f_g = 0.046\ Re_g^{-0.2}$$

$$G = \frac{\rho_l \; g_n \; D}{\rho_g \dot{V}_g^{\,2} f_g} \times 10^{-3}$$

$$F = \frac{\dot{\gamma}}{Re_g^{0.9}} \times \frac{\eta_l}{\eta_g} \times \left(\frac{\rho_g}{\rho_l}\right)^{1/2}$$

$$f_I = f_g \left[1 + 1400\, F \left\{1 - \exp\left[-\frac{(1+1400F)^{3/2}}{13.2\; F\; G}\right]\right\}\right]$$

$$\tau_I = 0.5\; f_I \; \rho_g \; \dot{V}_g^{\,2}$$

$$\tau_I^+ = \frac{\rho_l \; \tau_I}{[\rho_l \; (\rho_l - \rho_g)\eta_l' g_n]^{2/3}}$$

Value of the critical Reynolds number (Re_c) depends upon the value of τ_I^+.

For $\tau_I^+ > 9.04$, $Re_c = 50$

& For $\tau_I^+ \leq 9.04$, $Re_c = 1600 - 226\;\tau_I^+ + 0.667\;(\tau_I^+)^3$

If $Re < Re_c$ then ,

$$h^+ = 1.41\; Re_l^{-0.5} (\tau_I^+)^{0.5}$$

and if $Re > Re_c$ then ,

$$h^+ = (\tau_I^+) \left[\left(\frac{1.41}{Re^{0.5}}\right)^m + \left(\frac{0.071\; Pr_l^{0.5}}{Re_l^{1/24}}\right)^m \right]^{1/m}$$

where $m = 0.5(Pr_l+3)$

h_2 is related to h^+ by the following expression -

$$h_2 = h^+ \; k_l \left[\frac{\eta_l'^{\,2}}{\rho_l(\rho_l - \rho_g)\; g_n}\right]^{-1/3} \tag{3.8}$$

After knowing the values of h_1 & h_2 , h can be determined by

$$h_c = \text{MAX}\ [h_1, h_2] \tag{3.9}$$

3.4 Flooding Phenomenon :

This phenomenon becomes important for upward vapour flow. For low vapour flow rates the condensate runs freely from the bottom of the tube . However ,if the vapour velocity is gradually increased, at a certain point large waves and disturbances occur at the bottom of the tube with the liquid being held up periodically by the inflow of vapour . Some liquid is discharged from the top of the tube , this phenomenon is known as flooding and the lowest vapour velocity at which it occurs is known as the flooding velocity .

Flooding mass velocity is defined as ,

$$\dot{m}_V = \text{density x condensate flow velocity .} \tag{3.10}$$

Holmes (1950) data can be expressed by the following equation -

$$\dot{m}_V = \frac{80\ D^{0.30} \rho_1^{0.46}\ (1000\ \sigma)^{.09}\ \ \rho_g^{0.5}}{\eta_1^{0.14} (\cos\theta)^{0.32} (w_1/w_g)^{0.07}} \tag{3.11}$$

Here D - tube ID (mm)

ρ_1, ρ_g -densities (kg/m^3)

σ -surface tension (N/m)

η -viscosity (cP)

θ -taper of tube end from horizontal

w_1/w_g - weight ratio of condensate to vapour at the bottom of the tube

This flooding velocity should not exceed the above value of $\dot{m}_v$.

3.5 Classification of Condensers :

Condensers can be classified in various different ways:

Type of Industry : Chemical process industry , Power industry

Type of Condensation : Dropwise condensation , Filmwise condensation, direct contact condensation

Extent of condensation : Desuperheater condenser, Condenser, Condenser-subcooler, Desuperheater-condenser-subcooler .

Type of construction : Shell-and-tube, plate, spiral, air-cooled .

Orientation of condenser : Vertical, horizontal

Occurence of condensation : Inside tubes, outside tubes

Condensation controlling mechanism : Gravity controlled
Shear controlled

The details regarding various types of shell and tubes condensers can be obtained from Agrawal(1988).

3.6 Selection of a Condenser :

Selection of condenser types involves consideration of numerous conflicting requirements. The various classes of condensation are indicated in Flow-chart shown in Fig. 3.3 where a preliminary selection of a condenser type is to be evaluated. The Tables 3.1 to 3.4 then give the opinion on the applicability and predictability of the various types of condensers.The examination of Flow-chart and Tables should lead to proper selection of condenser type.

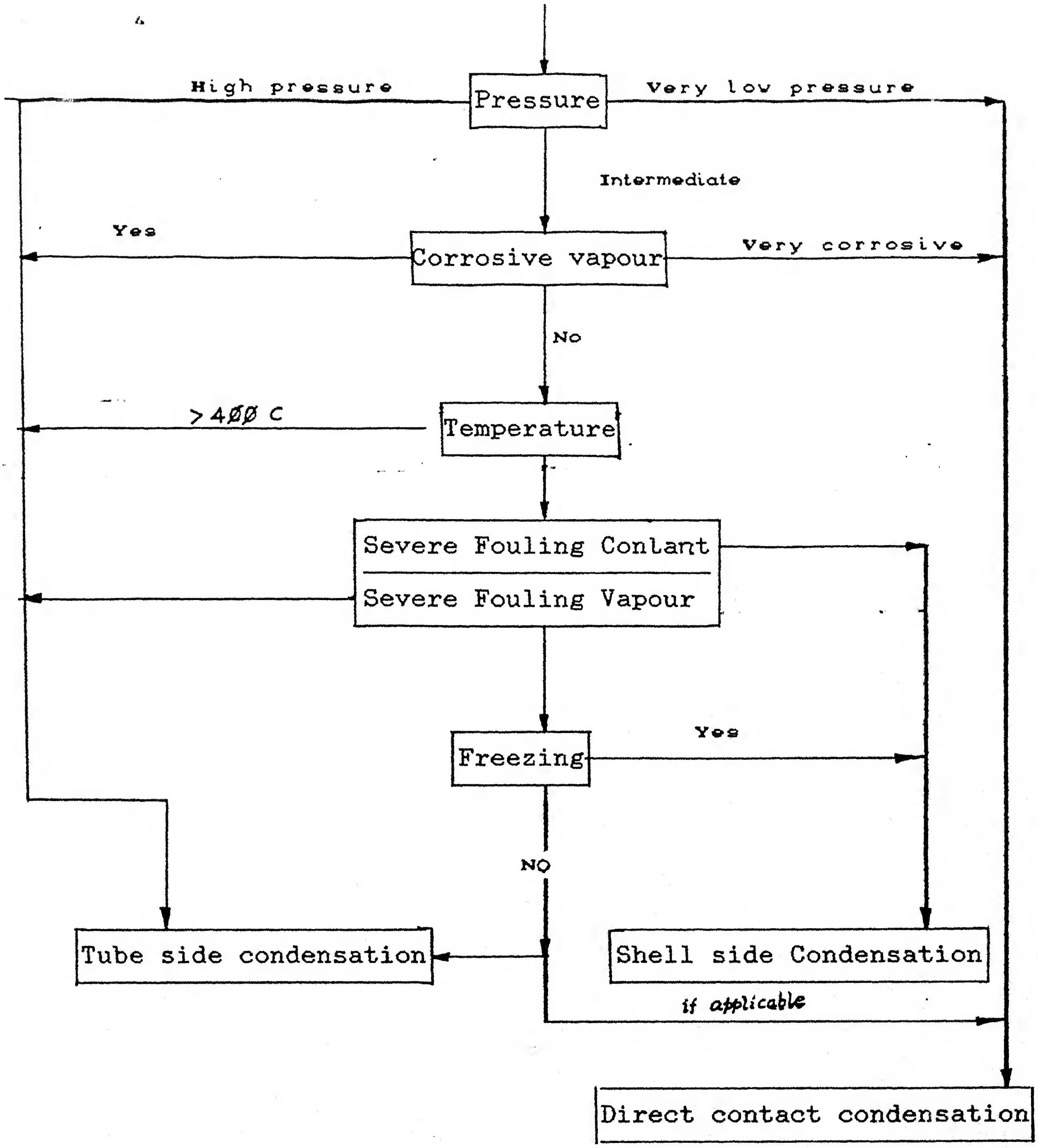


Fig. 3.3 Flow Chart for the Selection of a Condenser

Table 3.1: Total Tube-side Condensation

	Horizantal		Vertical-down flow		Vertical-up flow	
Single component Vapour	g*	av	g	av	f	b
Multi component vapour	f	b	g	b	f	c
Sub-cooled Condensate	p	x	g	av	x	x
Pressure drop						
High	g	b	g	c	x	c
Low	p	b	f	c	g	c
Coolant						
Liquid	g		g		g	
Gas	g		g		g	
Boiling	g		g		g	

Comments: Horizontal condensers have possibility of slugging.
Vertical down flow handles dirty or polymerising vapours.

Table 3.2: Partial Tube-side condensation

	Horizontal		Vertical down flow		Vertical up flow	
Single component vapour	g	av	g	av	x	x
Multi component vapour	p	b	g	b	x	x
Sub cooled condensate	g	av	g	av	x	x
Pressure drop						
High	g	b	g	c	p	c
Low	p	b	g	c	f	c
Coolant						
Liquid	g		g		g	
Gas	g		g		g	
Boiling	g		g		g	

Table 3.3: Total Shell-side Condensation

	Horizontal cross		Horizontal baffled		Vertical Down Flow		Vertical up flow	
Single component vapour	g	b	g	b	g	b	g	b
Multi component Vapour	g	b	g	b	g	c	p	c
Sub cooled Condensate	f	c	p	c	f	b	x	x
Pressure Drop								
High	g	b	g	b	g	c	x	x
Low	g	b	f	b	g	c	g	x
Coolant								
Liquid	g		g		g		g	
Gas	g		g		g		x	
Boiling	x		x		g		x	

Comments: Horizontal Cross can have possible venting problems:

Table 3.4: Partial Shell-side Condensation

	Horizontal cross		Horizontal baffled		Vertical Down Flow		Vertical up flow	
Single component vapour	p	b	p	b	p	b	x	x
Multi component Vapour	f	b	p	c	x	b	f	c
Sub cooled Condensate	g	b	g	b	x	av	f	b
Pressure Drop								
High	g	b	g	b	x	c	x	x
Low	g	b	p	b	f	c	g	x
Coolant								
Liquid	g		g		g		g	
Gas	g		g		g		x	
Boiling	x		x		g		x	

Comment: Horizontal cross can have possible venting problems.

**acceptability:* *g = good , f = Fair , p = poor*
x = not acceptable or not recommended.

predictability:
av = average ≈ 25 %
b = fair < 50 %
c = poor > 50 %
x = no method or not recommended

4. METHODOLOGY FOR THE DESIGN OF CONDENSERS

4.1 Introduction :

Overall design methodology remains the same as that for a STHE involving no phase change. The details regarding the design method of STHE without phase change can be found in Bhaskare (1986). Tube-side flow is well-defined and so can be easily computed. For shell-side Bell-Delaware-Method has been suitably modified to take into account the phase change part and for the final rating of the condensation zone successive summation method or Stepwise-Method has been used. The additional complications which arise in a condenser are as follows :

1. Sensible heat-transfer coefficients are rather low compared to condensation coefficients.

2. The non-linear heat release requires piecewise calculations instead of an overall calculations as is generally done for no phase change units.

3. The change in heat-transfer coefficient takes place at each step due to changes in physical properties of the mixture undergoing compositional changes (Gupta, 1986).

4.2 Logic of the Design Method :

The basic logical structure of the design process has

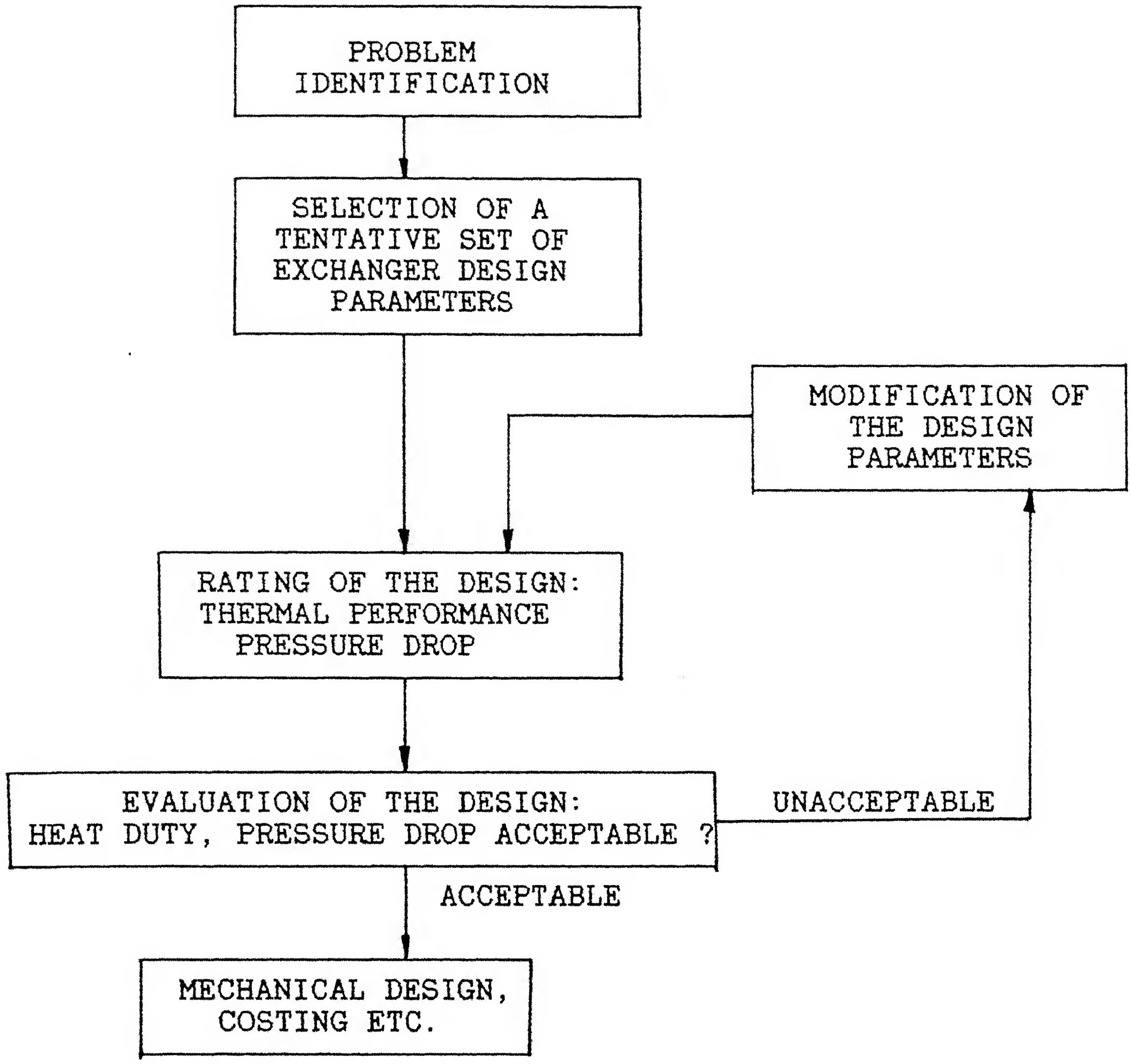


Fig. 4.1 Logic of the Design Method

been shown in Fig. 4.1. It involves rating both in terms of heat transfer as well as pressure drop calculations ,but in the present thesis the rules for the evaluation of pressure drop for the two phase flow are not included (Bell, 1986a)

4.3 Approximate Sizing of the Condensers :

An assumed or approximate design of condenser is necessary to start the iteration because the values of various heat transfer coefficients involved can not be determined unless the geometrical features of the condenser are known. The steps involved in obtaining an approximate design are as follows :

4.3.1 Selection of Condenser (See Chapter 3)

4.3.2 Determination of Heat-rate :

The heat duty which a heat exchanger is required to perform is given by :

$$\dot{q} = \dot{m}_h \left[c_{pg}(T_{hi}-T_{sat}) + \Delta h_v + c_{pl}(T_{sat}-T_{ho})\right]$$

$$=\dot{m}_c c_{pc}(T_{co}-T_{ci}) \qquad (4.1)$$

4.3.3 Overall LMTD :

By knowing or selecting the proper coolant temperatures the overall log mean temperature difference (LMTD) can be determined as follows :

For co-current flow :

$$\Delta T_{LM} = \frac{(T_{hi}-T_{ci}) - (T_{ho}-T_{co})}{\ln\left(\frac{T_{hi}-T_{ci}}{T_{ho}-T_{co}}\right)} \qquad (4.2a)$$

For counter flow:

$$\Delta T_{LM} = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln \frac{T_{hi} - T_{co}}{T_{ho} - T_{ci}}} \tag{4.2b}$$

4.3.4 Overall Heat Transfer Coefficient:

This should be estimated from previous experience of the designer or from Table 4.1 .

4.3.5 Approximate Area :

The approximate area is calculated using the following equation :

$$A_o = \frac{\dot{q}}{U_o . \Delta T_{LM}} \tag{4.3}$$

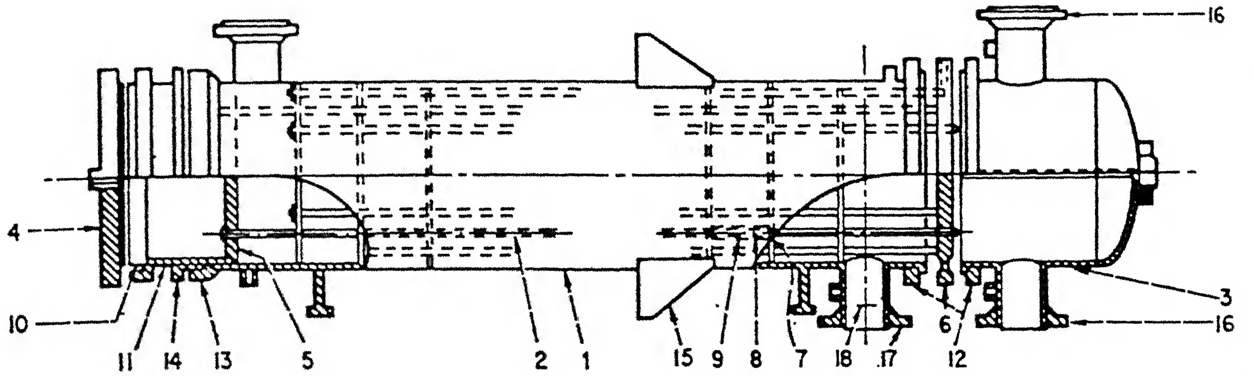
4.3.6 Geometrical Features :

After determining the area needed to satisfy heat transfer duty requirements, the geometrical features of the heat exchanger like tubesize, tube-length, shell-size, pitch and arrangement of baffles can be determined as described in the following section.

4.4 <u>Shell-side and Tube-side Parameters</u> :

The constructional features of STHE are shown in Fig. 4.2. The surface area can be written as :

$$A_o = A_o(D_s, L_s, D_t, \text{type of pitch-layout}) \tag{4.4}$$



1. Shell
2. Tubes
3. Channel

4. Floating-head cover
5. Floating tubesheet
6. Stationary tubesheet

7. Baffles
8. Spacers
9. Tie rods

10. Floating-head clamp
11. Floating tubesheet skirt
12. Flanges

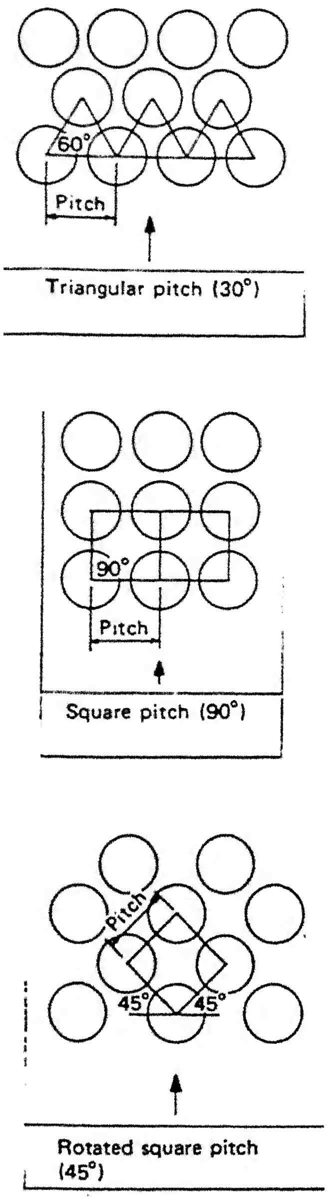
13. Stuffing-box flange
14. Gland follower
15. Supports

16. Tubeside nozzles
17. Shellside nozzles
18. Impingement plate

Fig. 4.2 Nomenclature for Shell and Tube Heat Exchanger Components

Table 4.1 : Approximate Values of Overall Coefficients

vapour	coolant	U W/sq-m/k
alcohol	*water*	50-1100
dowtherm	*tall oil*	40-450
dowtherm	*dowtherm*	450-680
high boiling hydrocarbons under vaccum	*water*	100-280
low boiling hydrocarbons	*water*	450-1140
organic solvents	*water*	550-1140
hydrocarbons	*oil*	140-230
kerosene	*water*	170-370
kerosene	*oil*	110-170
naphtha	*water*	280-430
naphtha	*oil*	110-170
steam	*feed water*	2200-5700
vegetable oils	*water*	110-280
organic steam, azeotrope	*water*	220-450
air coolers		
steam	*air*	730-800
ammonia	*air*	550-680
light hydrocarbon	*air*	450-540
light naphtha	*air*	400-450
freon	*air*	340-450
heavy naphtha	*air*	340-400



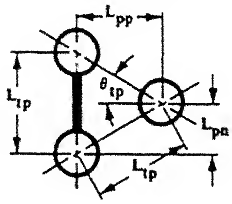
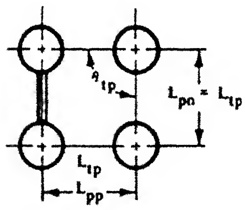
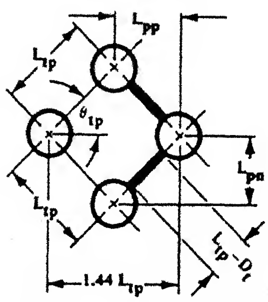
Tube layout geometry basic parameters			
Cross flow →	θ_{tp}	L_{tp}	L_{pp}
	30°	$0.5L_{tp}$	$0.866L_{tp}$
	90°	L_{tp}	L_{tp}
	45°	$0.707L_{tp}$	$0.707L_{tp}$

Fig. 4.3 Pitch Layout Angle

The type of pitch-layout is characterized by an angle θ_{tp} shown in Fig. 4.3. The relation between the heat-transfer area A_o, and other parameters of Eq. 4.4 is given by

$$A_o = 10^{-6} A^* \left[L_{ta} (D_{ctl})^2 \right] \quad m^2 \tag{4.5}$$

The tube-layout density parameter, A^* is defined as

$$A^* = 0.78 \pi \left(\frac{1}{C_1}\right) \frac{D_t}{(L_{tp})^2} \quad mm^{-1} \tag{4.6}$$

$C_1 = 1.0$ for $\theta_{tp} = 45^\circ$ or 90°

$C_1 = 0.866$ for $\theta_{tp} = 30^\circ$.

4.4.1 Shell-side Parameters :

The detailed description regarding bundle-types, bundle-shell-clearances and baffle geometry are available in the Refs. Bhaskare(1986) and HEDH(1983,Section 3.3.5 and 3.3.10).

To compute the coefficients for heat transfer the calculation of various flow areas and correction factors is essential. The cross-flow area at shell-centerline within one baffle-spacing is given by

$$S_m = L_{bc} \left[L_{bb} + \frac{D_{ctl}}{L_{tp,eff}} (L_{tt} - D_t) \right] \quad mm^2 \tag{4.7}$$

where $L_{tp,eff}$ = effective tube pitch

$= L_{tp}$ for 30° and 90° layout

$= 0.707 \times L_{tp}$ for 45° layout

The details regarding various leakage-streams and Bell-Delaware Method as suggested by Tinker have been discussed in Bell(1986). The various leakage areas, viz., baffle window flow

area, bundle to shell bypass area, shell to baffle leakage area, tube to baffle hole leakage area and associated correction factors j_c(baffle-window correction factor), j_l(baffle leakage correction factor), j_b(baffle bypass correction factor), j_r(adverse temperature gradient correction factor) and j_s(heat transfer correction factor for unequal end baffle spacing)can be calculated by the procedures given in Bhaskare(1986) and Taborek (1983).

The shell-side dimensionless parameters are :

1. Shell-side Reynolds Number :

The Shell-side mass velocity is given by

$$\dot{m}_s = \frac{\dot{M}_s}{S_m} \times 10^{-6} \quad kg/m^2 sec \tag{4.8}$$

The shell-side Reynolds Number is given by

$$Re_s = D_t \dot{m}_s / \eta_s \tag{4.9}$$

2. Shell-side Prandtl Number is given by

$$Pr_s = \frac{c_{ps}\ \eta_s}{k_s} \times 10^{-3} \tag{4.10}$$

4.4.2 Tube-side Parameters :

1. Tube-side Passes :

The number of tube-side passes is determined on the basis of flow velocity in the tubes. The present expert system can design a heat exchanger with only one tube side pass.

Mass-velocity in tubes is given by

$$\dot{m}_t = \frac{\dot{M}_t \times 10^6}{(A_{tot} / N_{tp})} \qquad (4.11)$$

Tube-side Reynolds number is given by

$$Re_t = \frac{(D_t - 2t_t)\ \dot{m}_t}{\eta_t} \qquad (4.12)$$

Tube-side Prandtl number is given by

$$Pr_t = \frac{C_{pt}\ \eta_t}{k_t} \times 10^{-3} \qquad (4.13)$$

4.5 Shell-side Heat Transfer Coefficient :

The basic equation for calculating the effective shell-side heat-transfer coefficient is given by

$$h_s = h_{ideal}\ j_c\ j_l\ j_b\ j_s\ j_r \qquad (4.14)$$

where h_{ideal} is the heat transfer coefficient for an ideal tube bank and is determined as described below.

4.5.1 Condensation Coefficient :

If shell-side condensation is going on, then h_{ideal} is determined by the expressions given in Section 3.3.

4.5.2 No Phase-change Coefficient :

If tube-side condensation is going on and coolant is flowing on the shell-side, then in the condensation zone coolant (shell-side) heat transfer coefficient is obtained from the j-factor curves given in HEDH(1983). The ideal tube bank factor is written as

$$j_i = j_i\left[Re_s,\ \frac{L_{tp}}{D_t}\right] \qquad (4.15)$$

For $\frac{L_{tp}}{D_t}$ = 1.25, the fitted equations for j_i are :

For θ_{tp} = 30° staggered :

$$\log_{10} j_i = 0.053\, x^2 - 0.7965\, x + 0.1999 \qquad (4.16)$$

For θ_{tp} = 45° staggered :

$$\log_{10} j_i = 0.0576\, x^2 - 0.8282\, x + 0.3 \qquad (4.17)$$

For θ_{tp} = 90° inline :

$$\log_{10} j_i = 0.05386\, x^2 - 0.7543\, x \qquad (4.18)$$

where $x = \log_{10}(Re_s)$

$$h_{s,ideal} = j_i\, C_{ps}\, \dot{m}_s\, (Pr_s)^{-2/3}\, (\phi_s)^r \qquad (4.19)$$

where $(\phi_s)^r$ = viscosity correction factor that accounts for the viscosity gradient at the tube-wall temperature versus the viscosity at the average bulk fluid temperature η_s. The term $(\phi_s)^r$ is computed as follows :

For liquids :

$$(\phi_s)^r = \left[\frac{\eta_s}{\eta_{sv}}\right]^{0.14} \qquad (4.20)$$

Tube-wall temperature is taken equal to condensing temperature in the condensing zone.

Viscosity of fluid at different temperatures is estimated using

$$\eta = a\, T^b \qquad (4.21)$$

For gases :

Gas being cooled : $(\phi_s)^r = 1.0$ (4.22)

Gas being heated : $(\phi_s)^r = \left[\frac{T_{s,av} + 273.15}{T_v + 273.15}\right]^{0.25}$ (4.23)

In desuperheating zone whether it is shell-side condensation or tube side condensation, the shell-side heat transfer coefficient is calculated using Eqs. (4.16) to (4.19). However, If the condensation is taking place on the shell side the shell-side heat transfer coefficient in the subcooling zone is calculated using the following expressions :

In the laminar region :

$$h_l = 0.78\ k_l \left(\frac{g\ \rho_l^2}{\eta_l'^2}\right) \left[Pr_l \left(\frac{\eta_l'^2}{g\ \rho^2}\right)^{1/3} \frac{1}{L}\right]^{1/3} Re^{1/9} \qquad (4.24)$$

where L is heat transfer length in m in subcooling zone.

The transition region is where $Re_l > Re_u$ and Re_u is the critical value of Re_l:

$$Re_u = 2460\ (Pr)^{-0.65}$$

Here,

$$h_l = 0.032\ k_l \left(\frac{g\ \rho^2}{\eta'^2}\right)^{1/3} Re_l^{0.2}\ Pr_l^{0.34} \ldots\ldots\ldots\ldots\ldots (4.25)$$

In the turbulent region, $Re_l > 2300.0$,

$$h_l = 5.7 \times 10^{-3}\ k_l \left(\frac{g\rho_l^2}{\eta_l'^2}\right) \qquad (4.26)$$

4.6 <u>Tube-side Heat Transfer Coefficient</u> :

4.6.1 Condensation Coefficient :

If it is a case of tube side condensation, then

$$h_t = h_c \qquad (4.27)$$

and h_c (condensation coefficient) is obtained using the expressions given in Section 3.3 .

4.6.2 No Phase Change Coefficient :

The heat transfer coefficient for all cases of no phase change except subcooling is determined by j-factor curves as given in Section 4.5.2 .However, the fitted equation in this case is:

$$\log_{10} j_h = -0.2624\ x^2 + 3.273\ x - 7.412 \qquad (4.28)$$

where $x = \log_{10} Re_t$

The actual heat transfer coefficient is then determined by

$$h_t = j_h \frac{k_t}{D_t} (Pr_t)^{1/3} (\phi)^r \qquad (4.29)$$

where $(\phi)^r$ is to be determined for the tube-side fluid in a manner similar to Section 4.5.2 .

The tube side heat transfer coefficient for the tube side condensation case in subcooling zone is again computed by the Eqs. (4.24) to (4.26) .

4.7 <u>Overall Heat Transfer Coefficient</u> :

After having computed the Shell-side and the Tube-side heat transfer coefficient the overall heat transfer coefficient can be determined by using the equation :

$$U_o = \frac{1}{\frac{1}{h_s} + R_{fs} + \frac{(r_o - r_i)}{k_w} \left(\frac{2\ r_o \times 10^{-3}}{r_o + r_i}\right) + \left[R_{ft} + \frac{1}{h_t} \left(\frac{r_o}{r_i} \right)\right]} \quad .. \qquad (4.30)$$

This will be an average value if all the other

coefficients are taken as average value, e.g., in desuperheating and subcooling zones. For the condensation zone, it will be calculated at each step since the condensation coefficient is a strong function of vapour fraction.

4.8 Stepwise Method for Condensation Zone :

Figure 4.4 shows a condenser where condensation zone starts at section AA .The section AA is a known section where the temperature of coolant, temperature of condensing fluid (= condensing temperature) and physical properties are known.

At the beginning of condensation, i.e., at Section AA :

Vapour Fraction, y = 1.0

Consider the full condensation zone to be divided into n steps. Then for each step :

$$\delta y = \frac{y_{inlet\ zone} - y_{outlet\ zone}}{n} \tag{4.31}$$

$$= \frac{1 - 0.0}{n} = \frac{1}{n}$$

For ith step, the coolant inlet temperature $T_{c,in}$ and outlet temperature $T_{c,out}$ are shown in the Fig. 4.4.

(1) Average condensate flow rate per unit width for ith step is—

$$\Gamma_i = \frac{[1.0 - (y + \delta y/2)] \times \dot{m}}{\pi D_t\ N_t} \tag{4.32}$$

(2) Reynolds Number for ith step is

$$Re_i = \frac{4\ \Gamma_i}{\eta_l'} \tag{4.33}$$

Knowing Re_i condensing heat transfer coefficient and so overall heat transfer coefficient can be determined.

(3) Heat load per step is given by

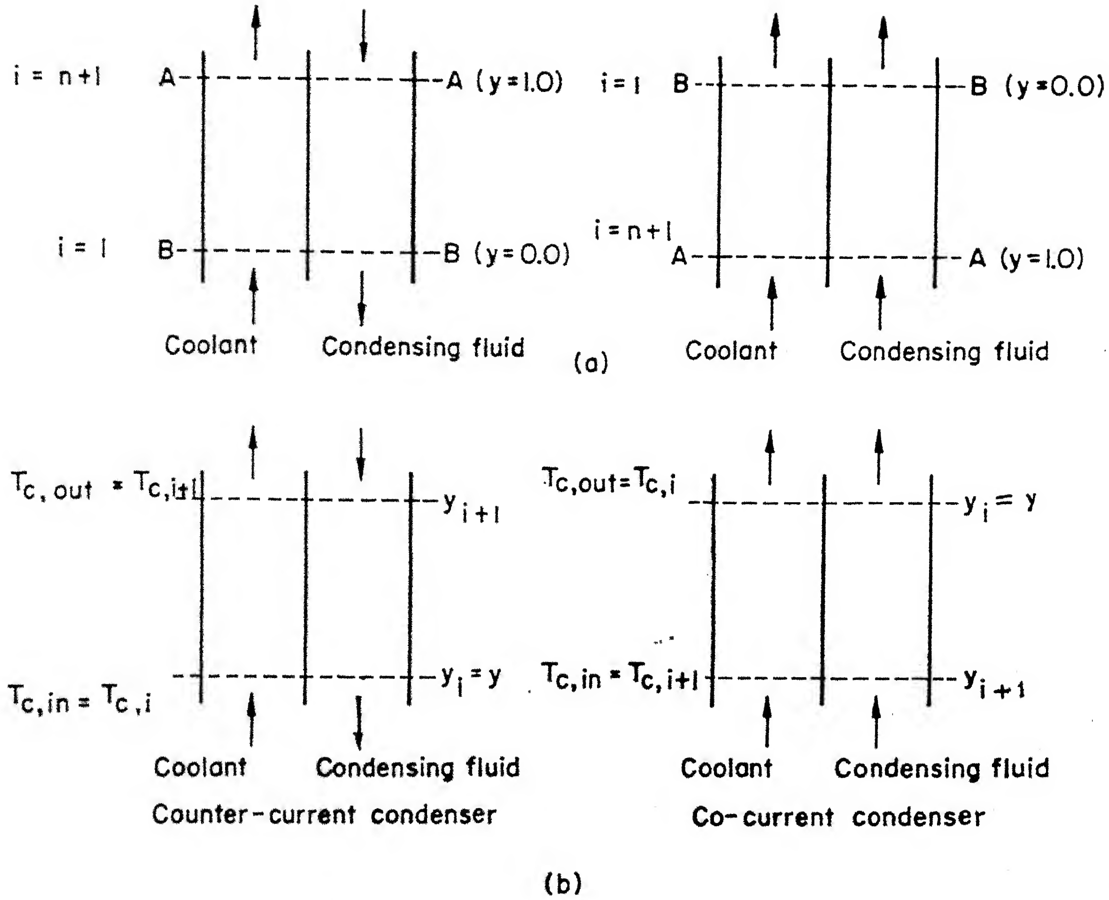


Fig. 4.4: Stepwise method for the condensation zone
a. Schematic of the condensation zone
b. Representation of i^{th} step indicating coolant temperatures and condensing-fluid's vapour fractions

$$\Delta q_i = \delta y . \Delta h_v . \dot{m} \qquad (4.34)$$

(4) At the inlet of ith step $T_{c,in}$ is known. At the outlet of ith step :

$$T_{c,out} = T_{c,in} + \frac{\Delta \dot{q}_i}{m_c c_{pc}} \qquad (4.35)$$

or, for ith step–

$$T_{c,i+1} = T_{c,i} \pm \frac{\Delta \dot{q}_i}{\dot{m}\ c_{pc}} \qquad (4.36)$$

where negative sign is for co-current flow and positive sign is for counter flow.

(5) Knowing Δq_i from step 3, area for any element can be calculated :

$$\Delta A_i = \frac{\Delta\ \dot{q}_i}{U_i\ .\ \Delta T_{LM,i}} \qquad (4.37)$$

where $\Delta T_{LM,i}$ is determined from Eqs. (4.2a) and (4.2b) .

(6) After calculating ΔA_i for each step, the area required for condensation zone is given by :

$$A_{con} = \sum_{i=1}^{n} \Delta A_i \qquad (4.38)$$

4.9 Overview of Rating Procedure for Calculating Area Required :

The rating problem can be expressed as in Table 4.2. Rating, in general, involves following steps :

4.9.1 Desuperheating Area Calculation :

Desuperheating heat load is given by :

$$\dot{q}_{ds} = \dot{m}\ c_{pg}(T_{ho} - T_{con}) \qquad (4.39)$$

Desuperheating zone will be at coolant inlet point for

Table 4.2 : Rating Problem

Rating Problem
Given : Process Specifications
Flow rates
Inlet temperatures
Outlet temperatures
Physical properties
Fouling characteristics
Geometry of Exchanger
Shell inside diameter
Outer tube limit
Tube diameter and layout
Baffle spacing and cut
Calculate : Area required

co-current heat exchanger and coolant outlet point in counter-current heat exchanger. Fig. 4.5 shows the schematics of co-current and counter-current heat exchangers. The terms co-current and counter-current just indicate the relative positions of the inlet and the outlet points of both the fluid streams and not the parallel flow. $T_{c\ i}, T_{con,i}, T_{con,o}$ and $T_{c\ o}$ have been indicated in the Fig. 4.5 .

$$T_{con,i} = T_{ci} + \frac{\dot{q}_{ds}}{\dot{m}_c\ c_{pc}} \qquad \text{(co-current flow)} \qquad (4.40a)$$

$$= T_{co} - \frac{\dot{q}_{sub} + \dot{q}_{con}}{\dot{m}_c\ c_{pc}} \qquad \text{(co-current flow)} \qquad (4.40b)$$

$$T_{con,i} = T_{ci} + \frac{\dot{q}_{sub} + \dot{q}_{con}}{\dot{m}_c\ c_{pc}} \qquad \text{(counter-flow)} \qquad (4.40c)$$

$$= T_{co} - \frac{\dot{q}_{ds}}{\dot{m}_c\ c_{pc}} \qquad \text{(counter-flow)} \qquad (4.40d)$$

Log mean temperature difference can be expressed in functional form as :

For co-current flow,

$$\Delta T_{LMds} = \Delta T_{LM}(T_{h\ i}, T_{con}, T_{c\ i}, T_{con,i}) \qquad (4.41a)$$

For counter flow,

$$\Delta T_{LMds} = \Delta T_{LM}(T_{h\ i}, T_{con}, T_{c\ o}, T_{con,i}) \qquad (4.41b)$$

LMTD correction factor for one tube pass and one shell pass heat exchanger is 1.0 .The detailed description of it is given in Bhaskare(1986). Now, desuperheating area is determined by :

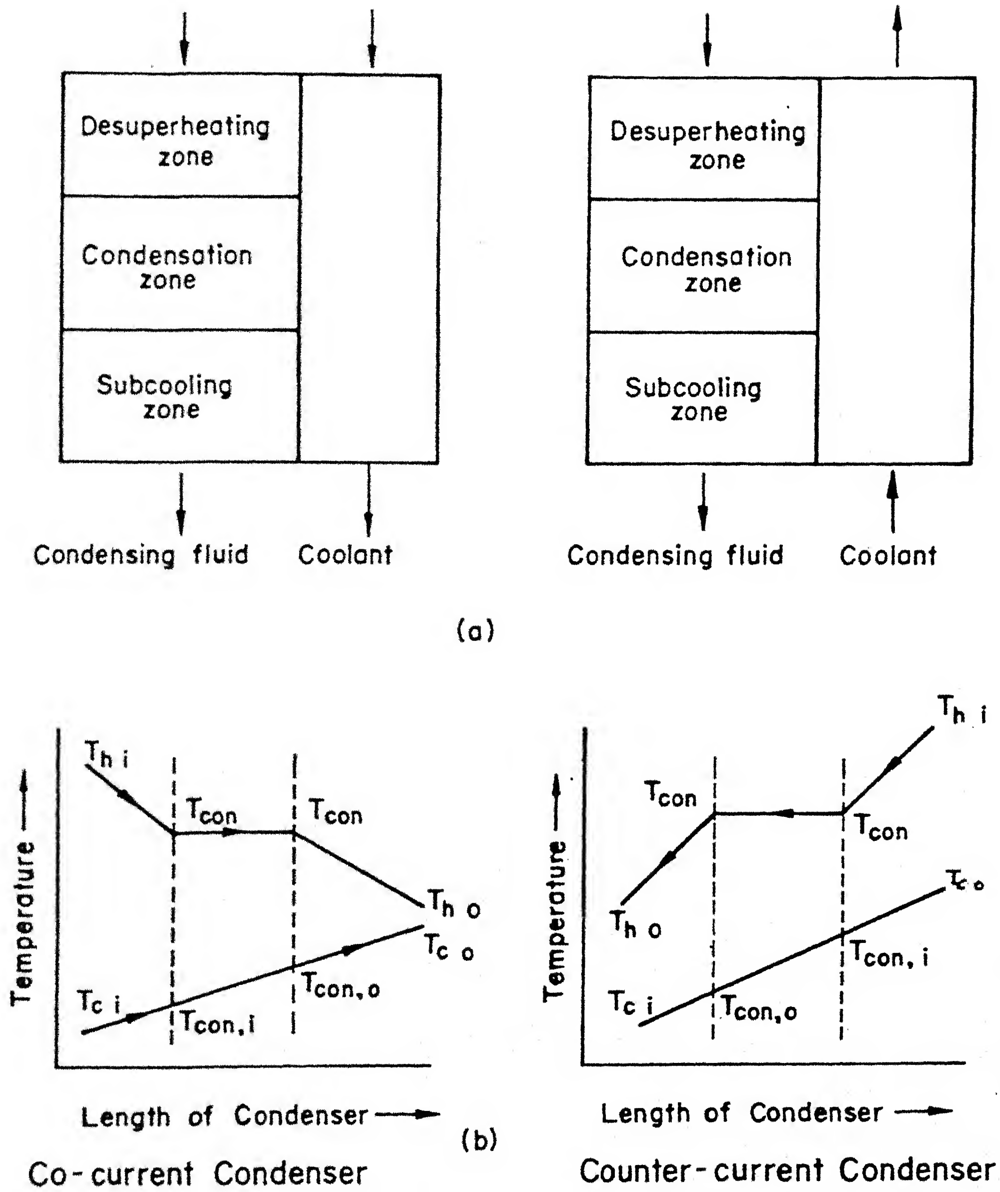


Fig. 4.5(a) Schematics of Various Heat Transfer Zones
(b) Temperature Profiles for Co-current and Counter-current Condensers in the absence of Non-condensables.

$$A_{desup} = \frac{\dot{q}_{ds}}{U_{desup}\, \Delta T_{LMds} F_c} \qquad (4.42)$$

where U_{desup} will be determined based on the procedure given in Section 4.7 .

4.9.2 Condensation Area :

The condensation area is calculated by the stepwise method as given in Section 4.6 .

4.9.3 Subcooling Area :

The subcooling heat load is given by :

$$\dot{q}_{sub} = \dot{m}\, c_{pl}\, (T_{con} - T_{h\ o}) \qquad (4.43)$$

The temperatures $T_{con,o}$ and so the LMTD can be determined on similar lines as for desuperheating area in Section 4.7.1 .

The overall heat transfer coefficient $U_{subcool}$ for subcooling zone can be detrmined based on the procedure given in Section 4.5 .So the subcooling area is given by :

$$A_{sub} = \frac{\dot{q}_{sub}}{U_{subcool}\, \Delta T_{LMsub}\, F_c} \qquad (4.44)$$

4.9.4 Total Area Required :

The total area required from the rating program is given by :

$$A = A_{desup} + A_{con} + A_{sub} \qquad (4.45)$$

5. RULE SETS OF THE EXPERT SYSTEM

5.1 Flow Chart for the Design :

Fig. 5.1 gives the flow-chart in brief for the design of condensers. The steps to be followed can be summarised as given below :

1. Decide about the type of condenser. This involves choice between shell-side and tube-side condensation and the selection regarding vertical or horizontal, co-current or counter-current (both pertaining to E-type shell) heat exchanger.

2. Estimate the approximate area from the property-data and specifications.

3. Decide about the type of bundle, baffle geometry and shell and tube geometry from the approximate area and the limitations imposed upon the design.

4. If the choice is vertical-upflow condenser involving tube-side condensation, then ensure that the tube-side mass velocity is less than the flooding mass velocity else modify the design by going back to Step 3.

5. Determine the various correction factors from the geometry of STHE and various flow areas.

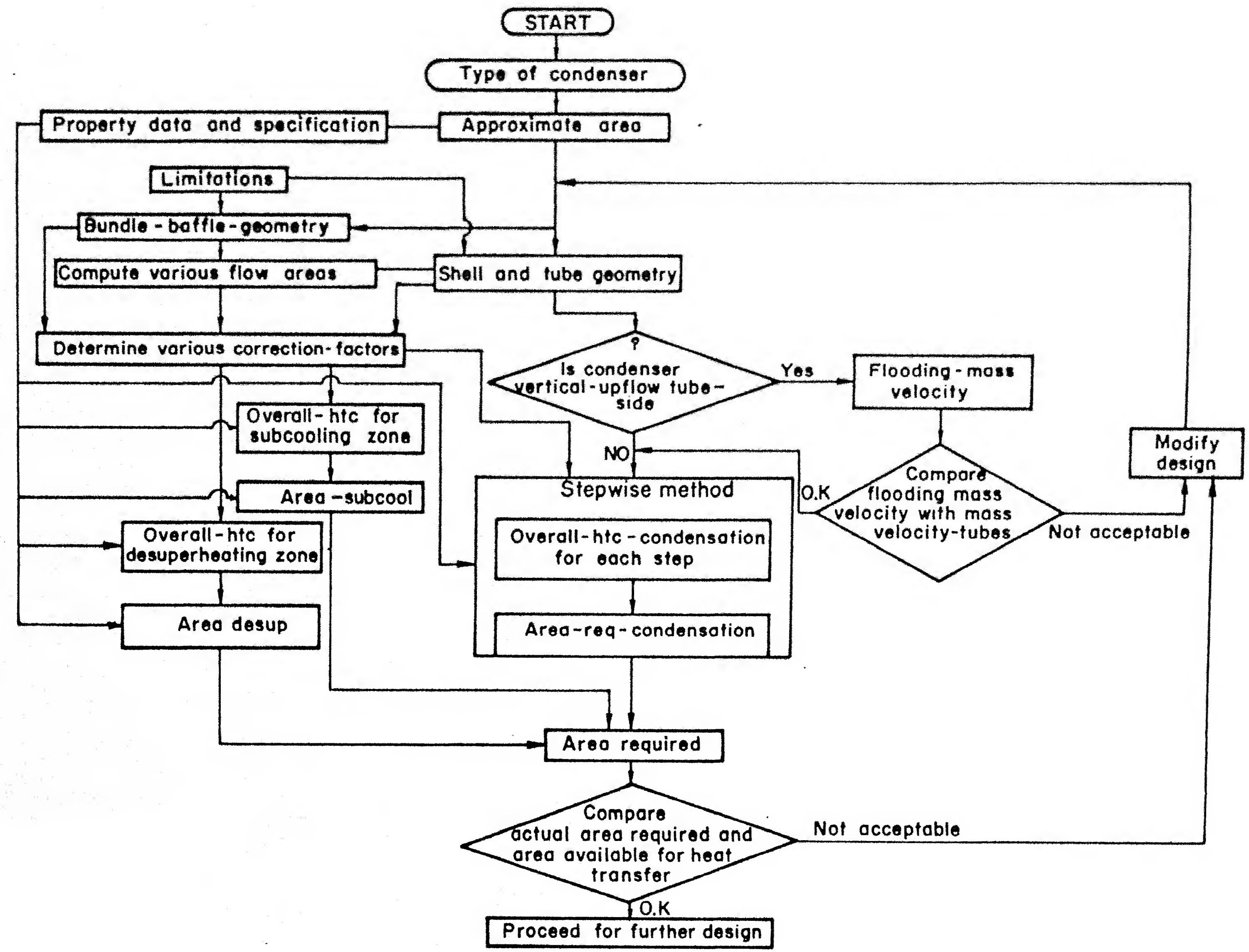
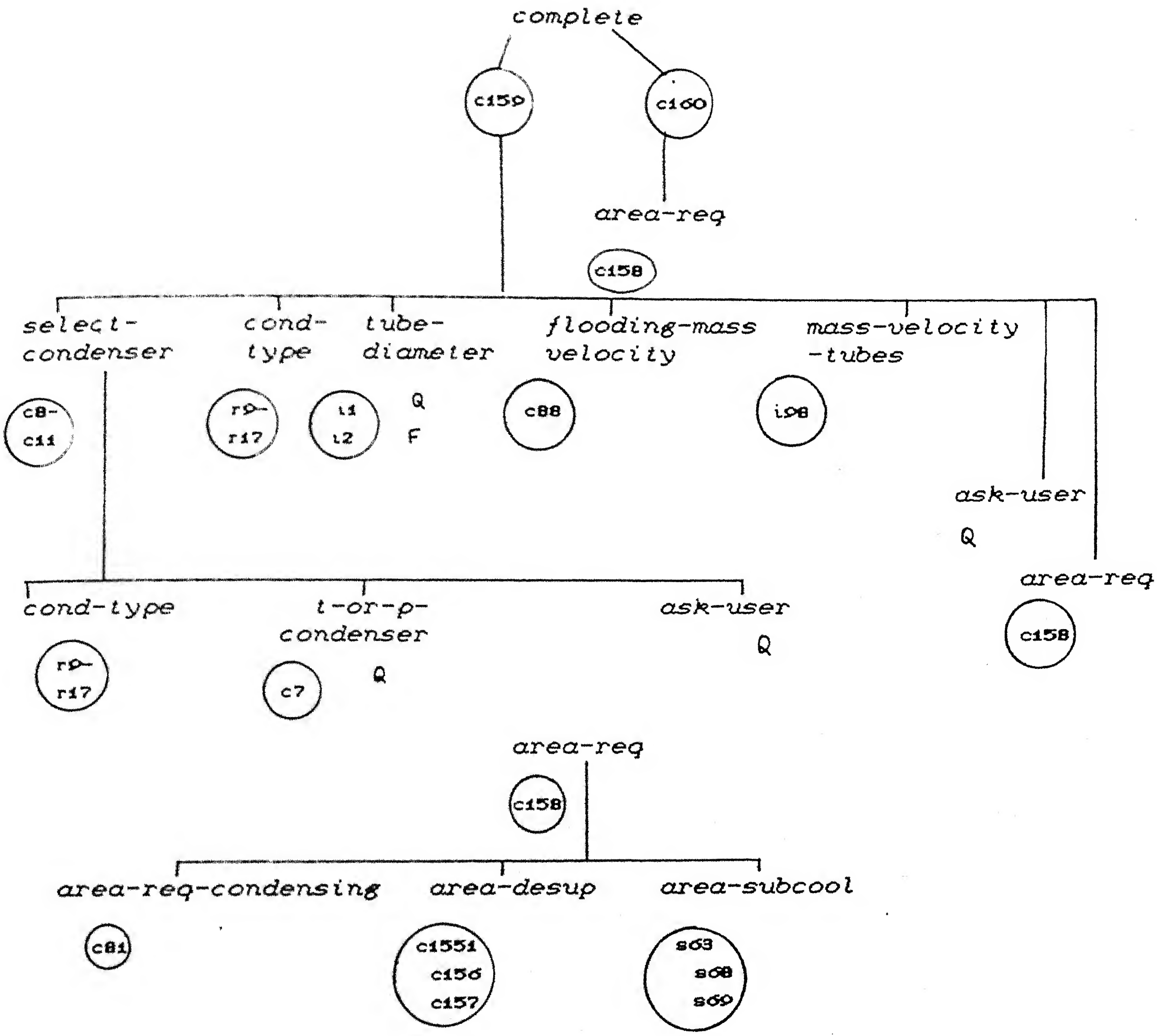
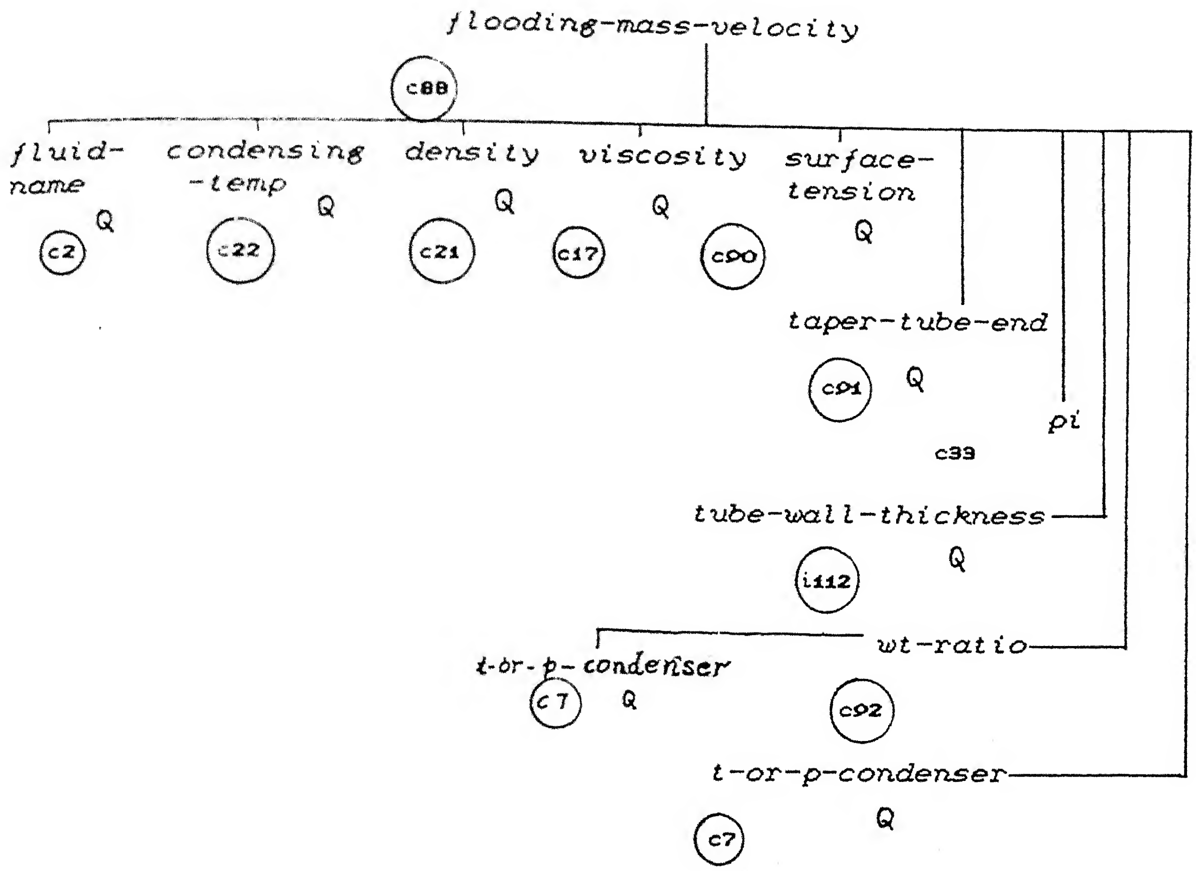
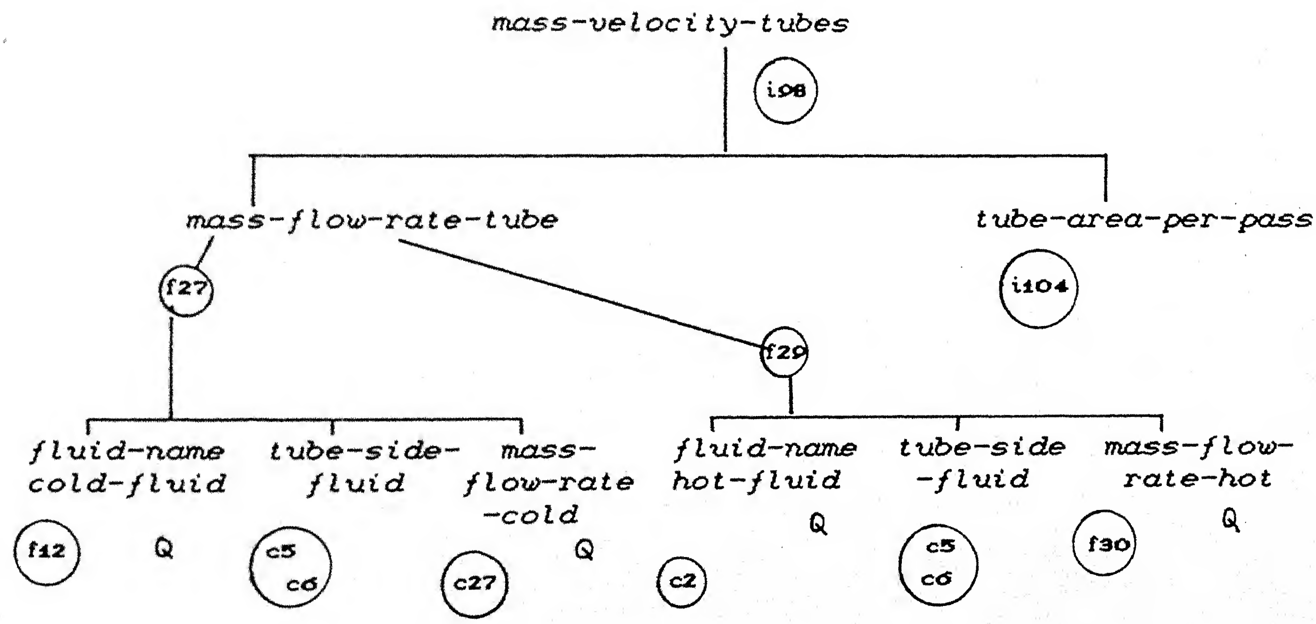
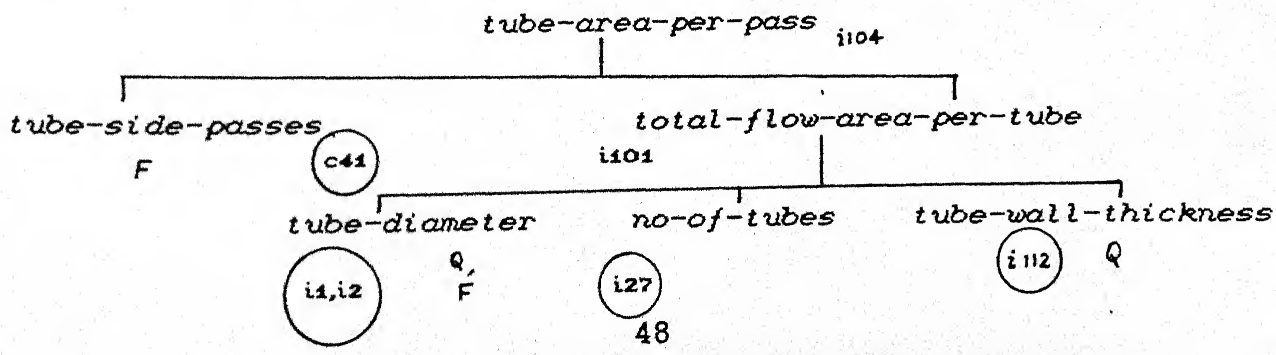


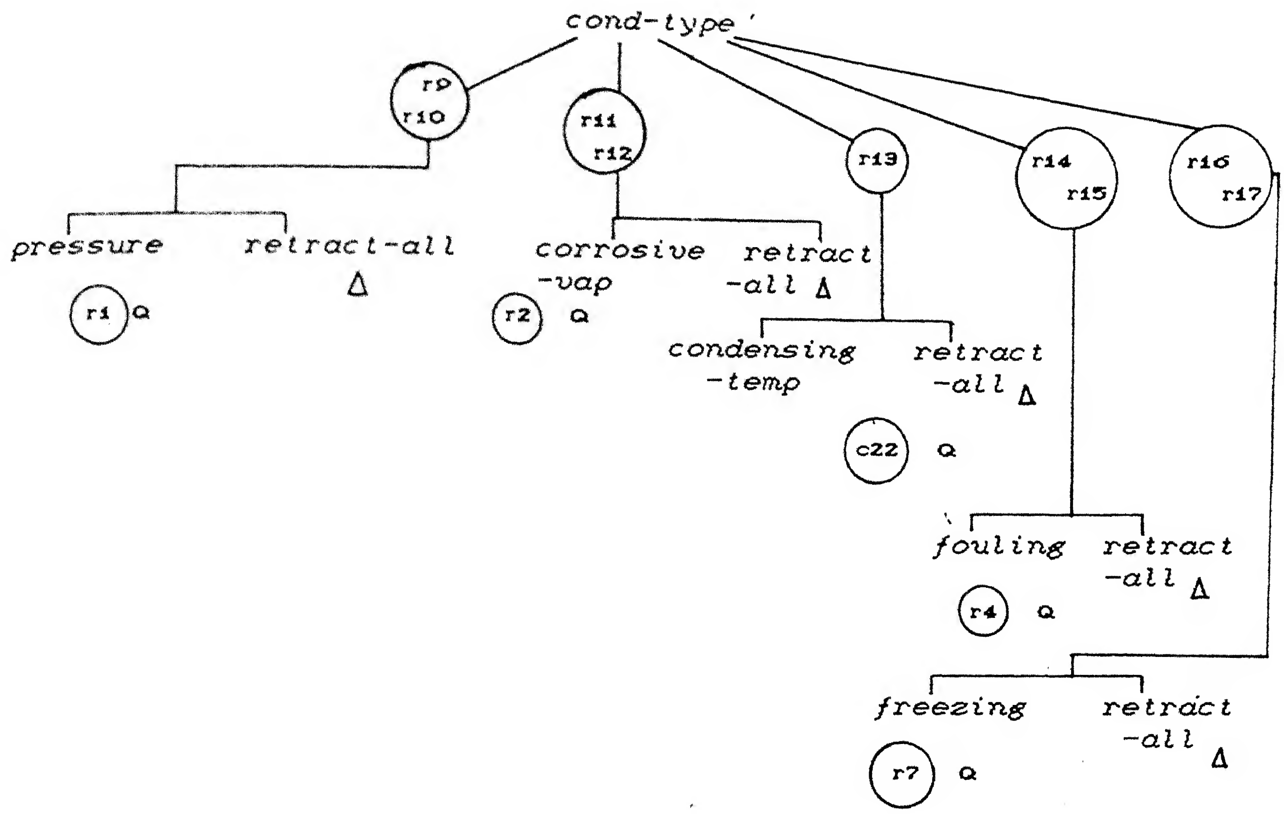
Fig. 5.1 Flow Chart for the Design of Vertical Condensers

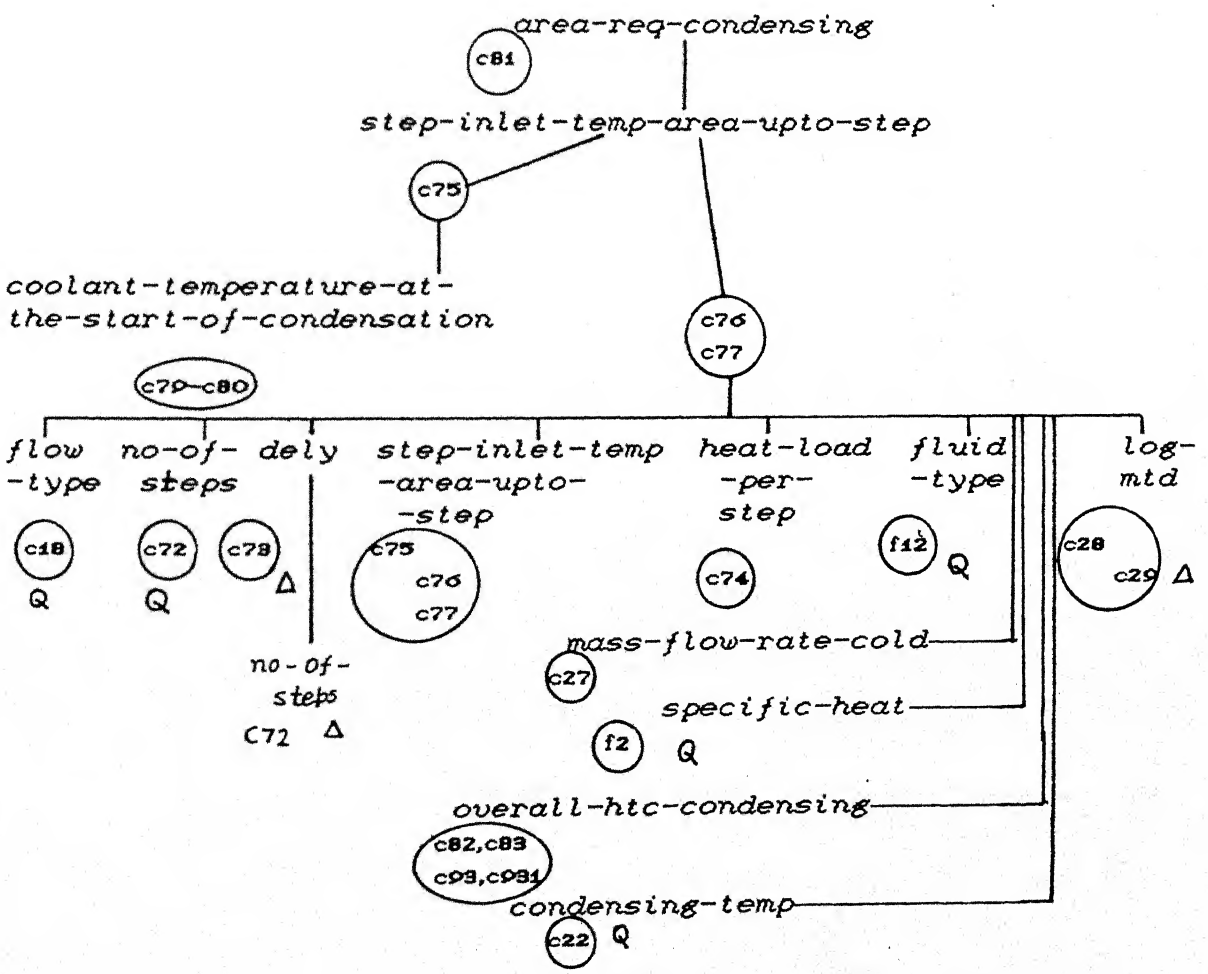

complete
c159
c160
area-req
c158
select-
condenser
c8-
c11
cond-
type
r9-
r17
tube-
diameter
t1
t2
Q
F
flooding-mass
velocity
c88
mass-velocity
-tubes
i98
ask-user
Q
area-req
c158
cond-type
r9-
r17
t-or-p-
condenser
c7
Q
ask-user
Q
area-req
c158
area-req-condensing
c81
area-desup
c1551
c156
c157
area-subcool
s63
s68
s69

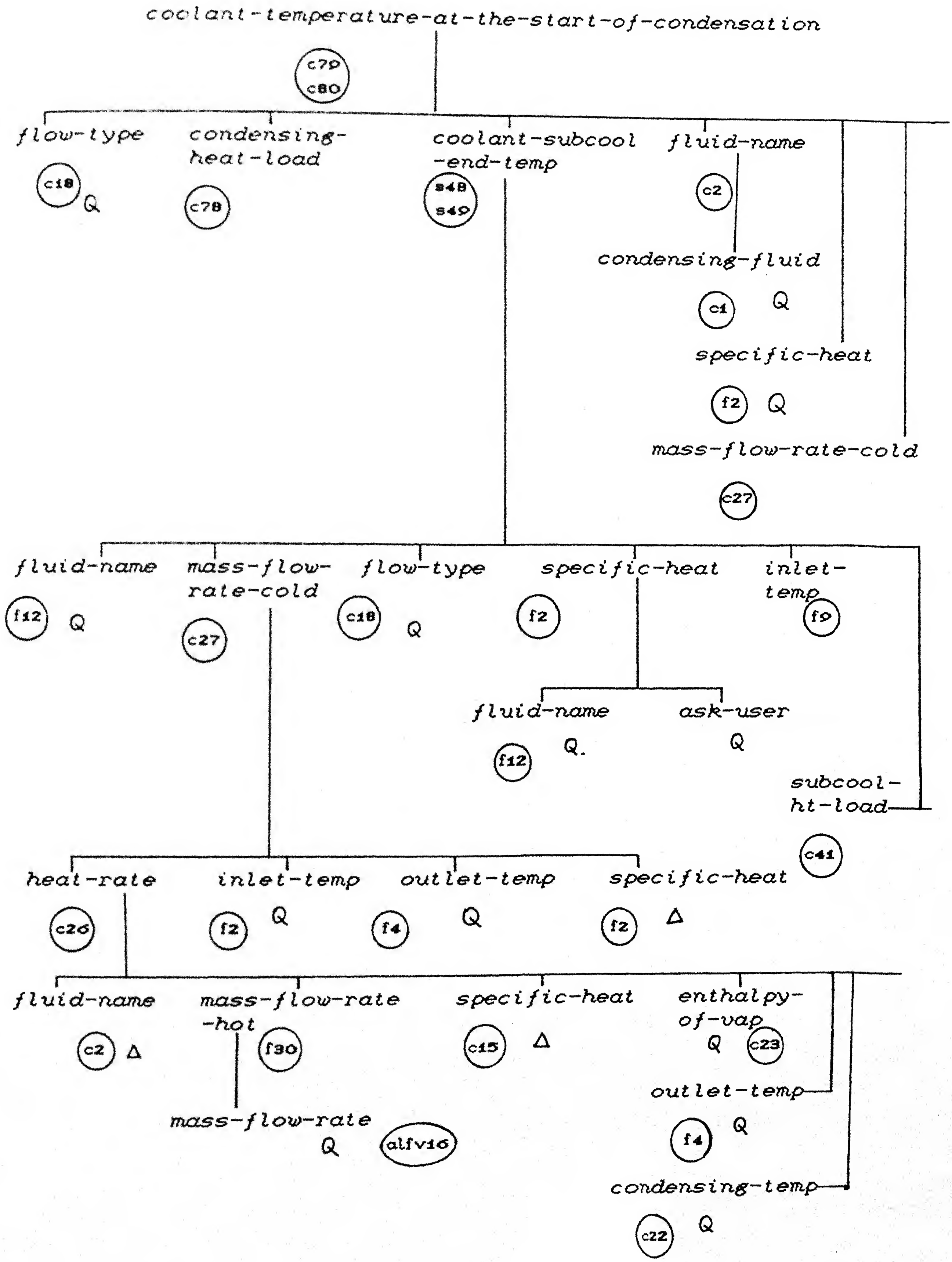

flooding-mass-velocity
c88
fluid-name
Q
c2
condensing-temp
Q
c22
density
Q
c21
viscosity
Q
c17
surface-tension
Q
c90
taper-tube-end
Q
c91
pi
c33
tube-wall-thickness
Q
i112
wt-ratio
c92
t-or-p-condenser
Q
c7
t-or-p-condenser
Q
c7

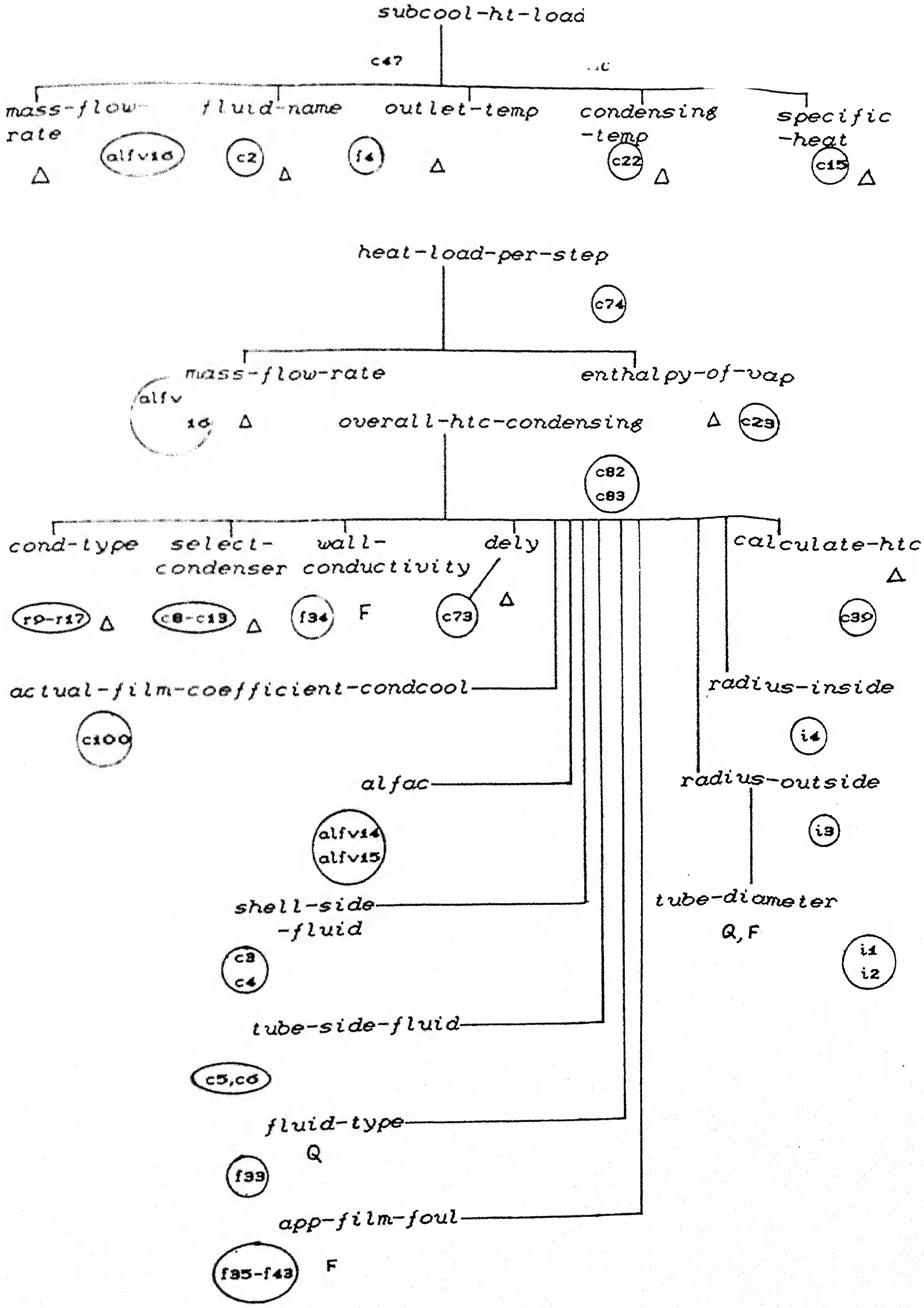

mass-velocity-tubes
i98
mass-flow-rate-tube
tube-area-per-pass
i104
f27
f29
fluid-name cold-fluid
Q
f12
tube-side-fluid
c5 c6
mass-flow-rate-cold
Q
c27
fluid-name hot-fluid
Q
c2
tube-side-fluid
c5 c6
mass-flow-rate-hot
Q
f30

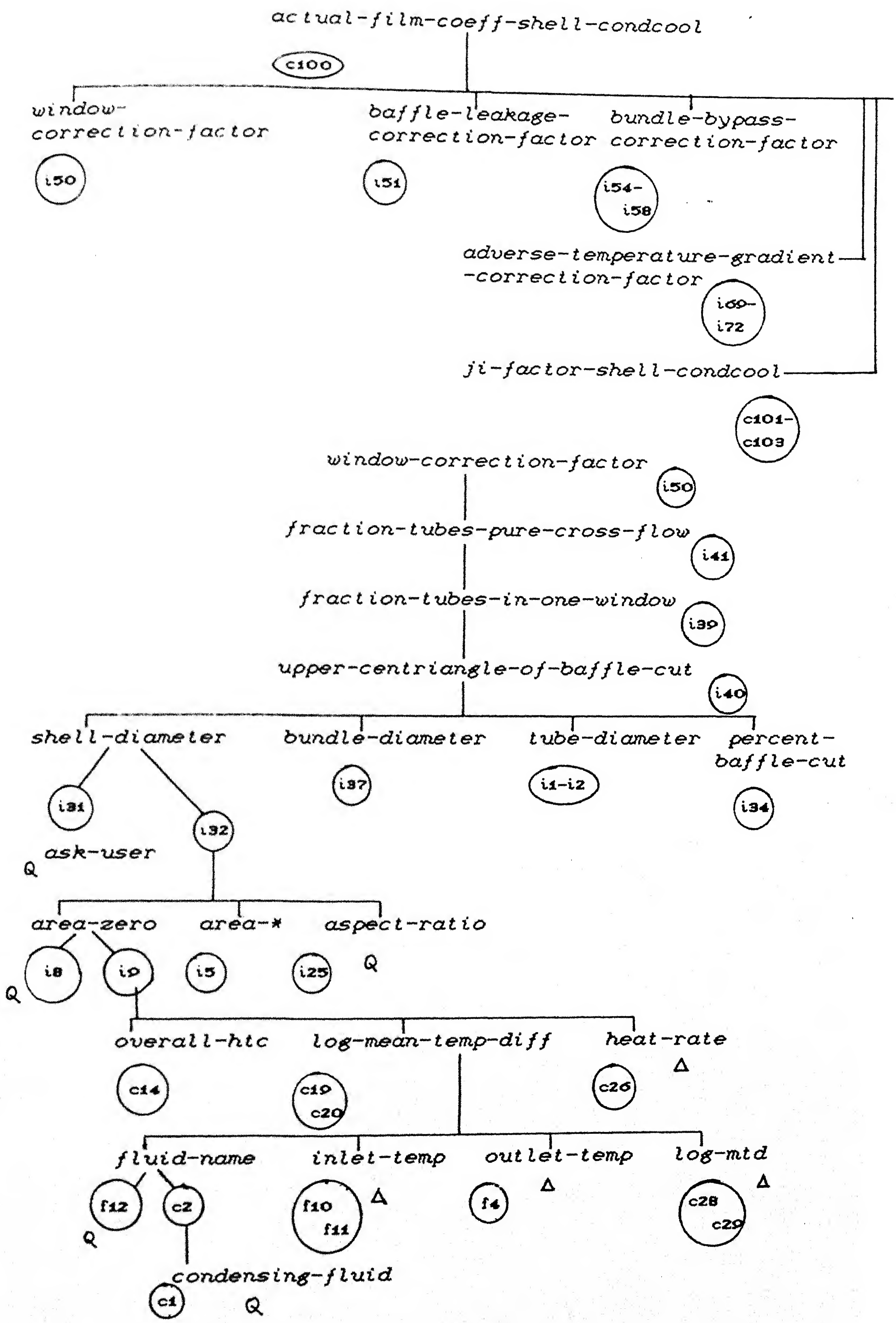

tube-area-per-pass
i104
tube-side-passes
F
c41
total-flow-area-per-tube
i101
tube-diameter
Q, F
i1,i2
no-of-tubes
i27
tube-wall-thickness
Q
i112


cond-type
r9 r10
r11 r12
r13
r14 r15
r16 r17
pressure
retract-all
r1 Q
corrosive -vap
retract -all
r2 Q
condensing -temp
retract -all
c22 Q
fouling
retract -all
r4 Q
freezing
retract -all
r7 Q

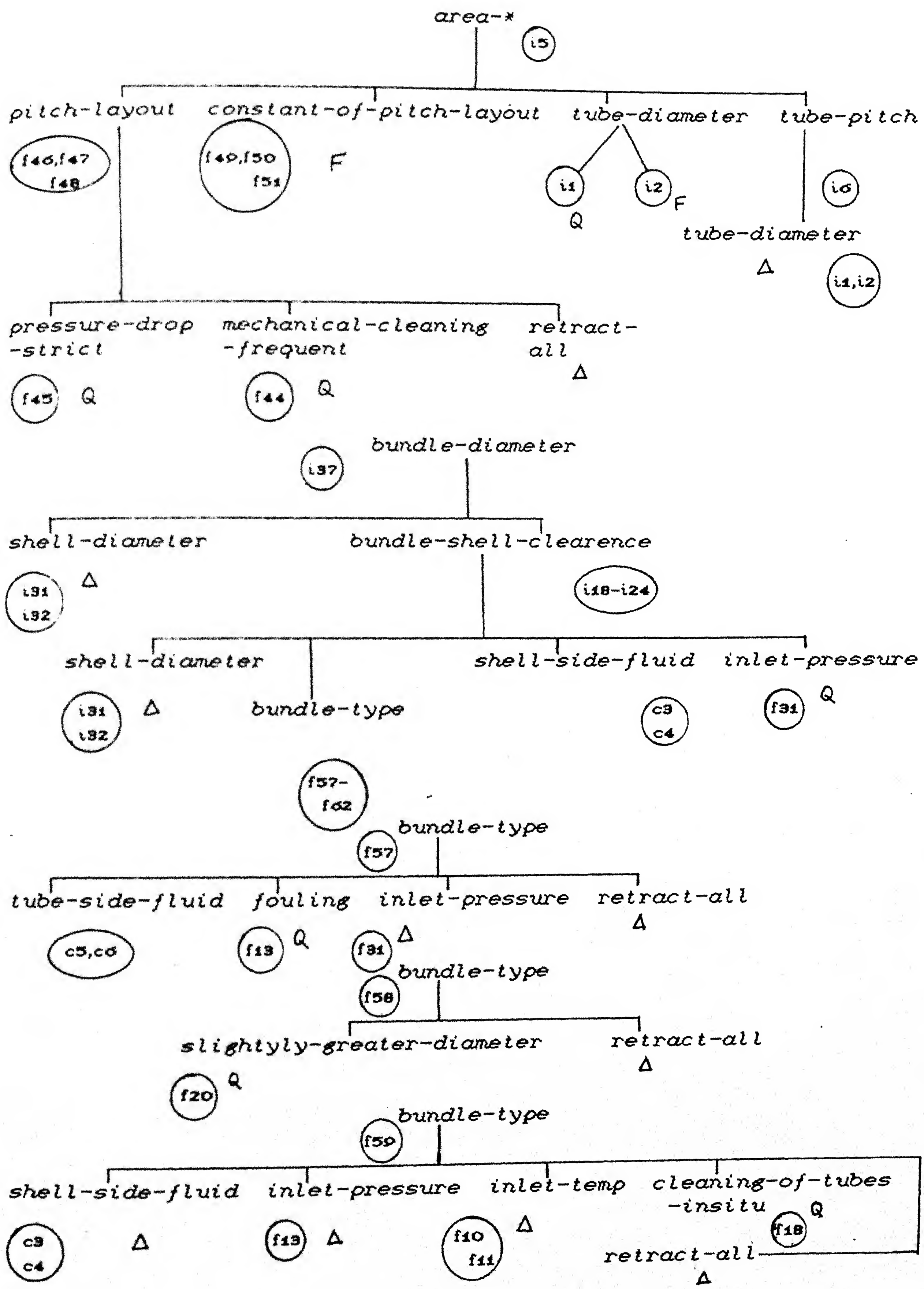

area-req-condensing
c81
step-inlet-temp-area-upto-step
c75
coolant-temperature-at-the-start-of-condensation
c76 c77
c79-c80
flow -type
no-of- steps
dely
step-inlet-temp -area-upto- -step
heat-load -per- step
fluid -type
log- mtd
c18 Q
c72 Q
c78
c75 c76 c77
c74
f12 Q
c28 c29
no-of- steps
C72
mass-flow-rate-cold
c27
specific-heat
f2 Q
overall-htc-condensing
c82,c83 c93,c931
condensing-temp
c22 Q

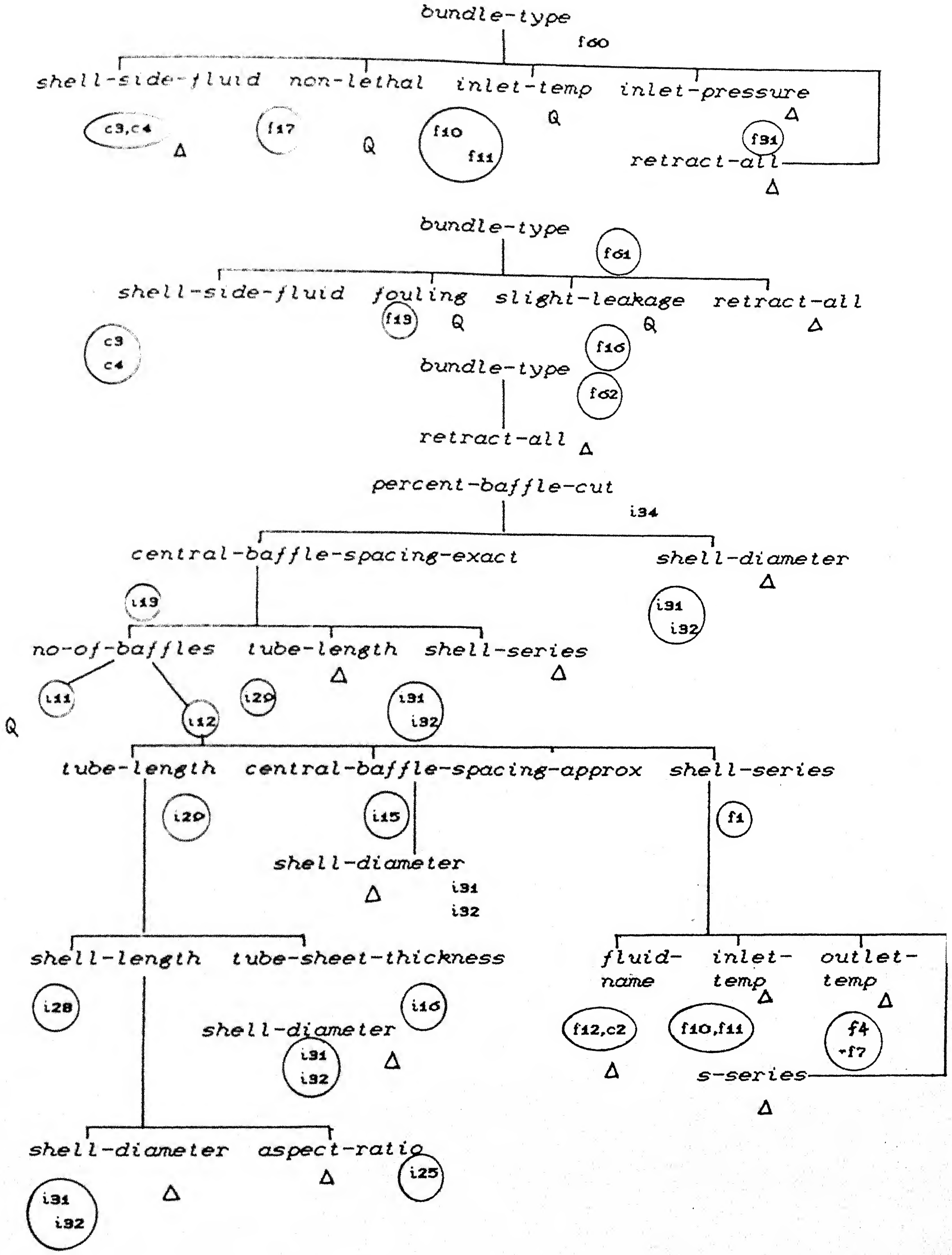

coolant-temperature-at-the-start-of-condensation
c79
c80
flow-type
c18
Q
condensing-heat-load
c78
coolant-subcool-end-temp
s48
s49
fluid-name
c2
condensing-fluid
c1
Q
specific-heat
f2
Q
mass-flow-rate-cold
c27
fluid-name
f12
Q
mass-flow-rate-cold
c27
flow-type
c18
Q
specific-heat
f2
inlet-temp
f9
fluid-name
f12
Q.
ask-user
Q
subcool-ht-load
c41
heat-rate
c26
inlet-temp
f2
Q
outlet-temp
f4
Q
specific-heat
f2
Δ
fluid-name
c2
Δ
mass-flow-rate-hot
f30
specific-heat
c15
Δ
enthalpy-of-vap
Q
c23
outlet-temp
f4
Q
mass-flow-rate
Q
alfv16
condensing-temp
c22
Q


subcool-ht-load
c47
mass-flow-rate
alfv16
fluid-name
c2
outlet-temp
f4
condensing-temp
c22
specific-heat
c15
heat-load-per-step
c74
mass-flow-rate
alfv 16
enthalpy-of-vap
c23
overall-htc-condensing
c82 c83
cond-type
r9-r17
select-condenser
c8-c13
wall-conductivity
f34
F
dely
c73
calculate-htc
c39
actual-film-coefficient-condcool
c100
radius-inside
i4
alfac
alfv14 alfv15
radius-outside
i3
shell-side-fluid
c3 c4
tube-diameter
Q, F
i1 i2
tube-side-fluid
c5,c6
fluid-type
Q
f33
app-film-foul
f35-f43
F

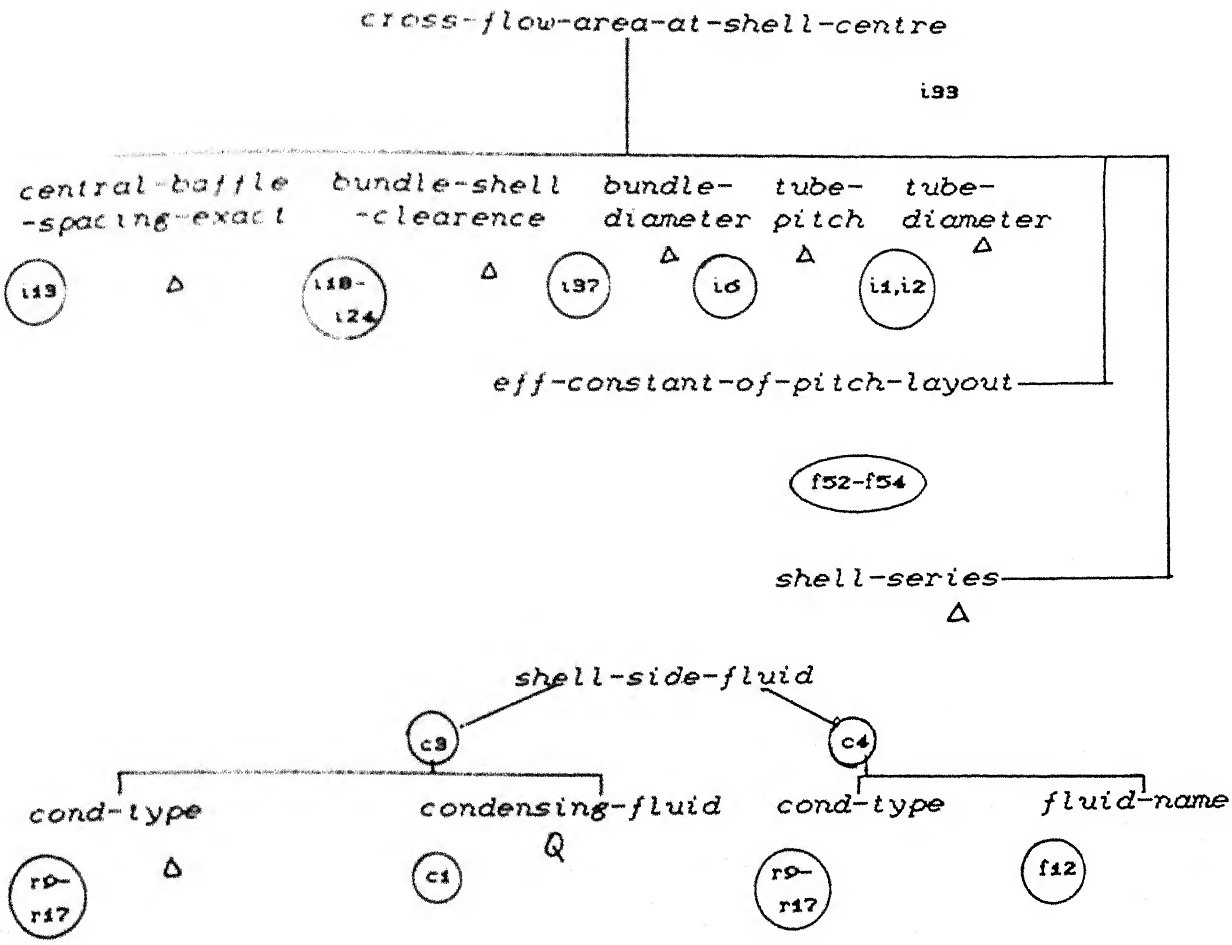


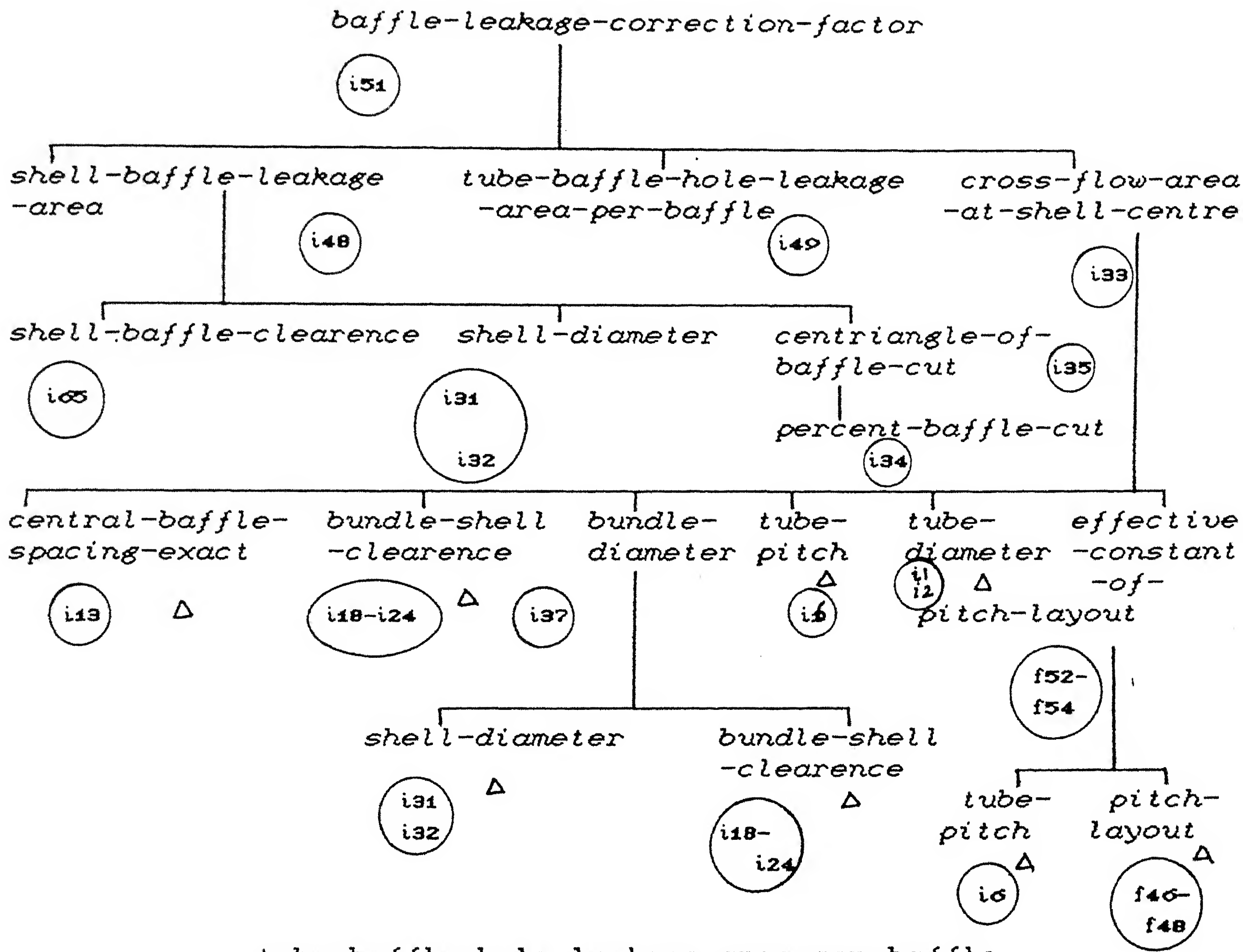
actual-film-coeff-shell-condcool
c100
window-correction-factor
i50
baffle-leakage-correction-factor
i51
bundle-bypass-correction-factor
i54-i58
adverse-temperature-gradient-correction-factor
i69-i72
ji-factor-shell-condcool
c101-c103
window-correction-factor
i50
fraction-tubes-pure-cross-flow
i41
fraction-tubes-in-one-window
i39
upper-centriangle-of-baffle-cut
i40
shell-diameter
bundle-diameter
tube-diameter
percent-baffle-cut
i31
i32
i37
i1-i2
i34
ask-user
Q
area-zero
area-*
aspect-ratio
i8
i9
i5
i25
Q
Q
overall-htc
log-mean-temp-diff
heat-rate
c14
c19 c20
c26
fluid-name
inlet-temp
outlet-temp
log-mtd
f12
c2
f10 f11
f4
c28 c29
Q
condensing-fluid
c1
Q

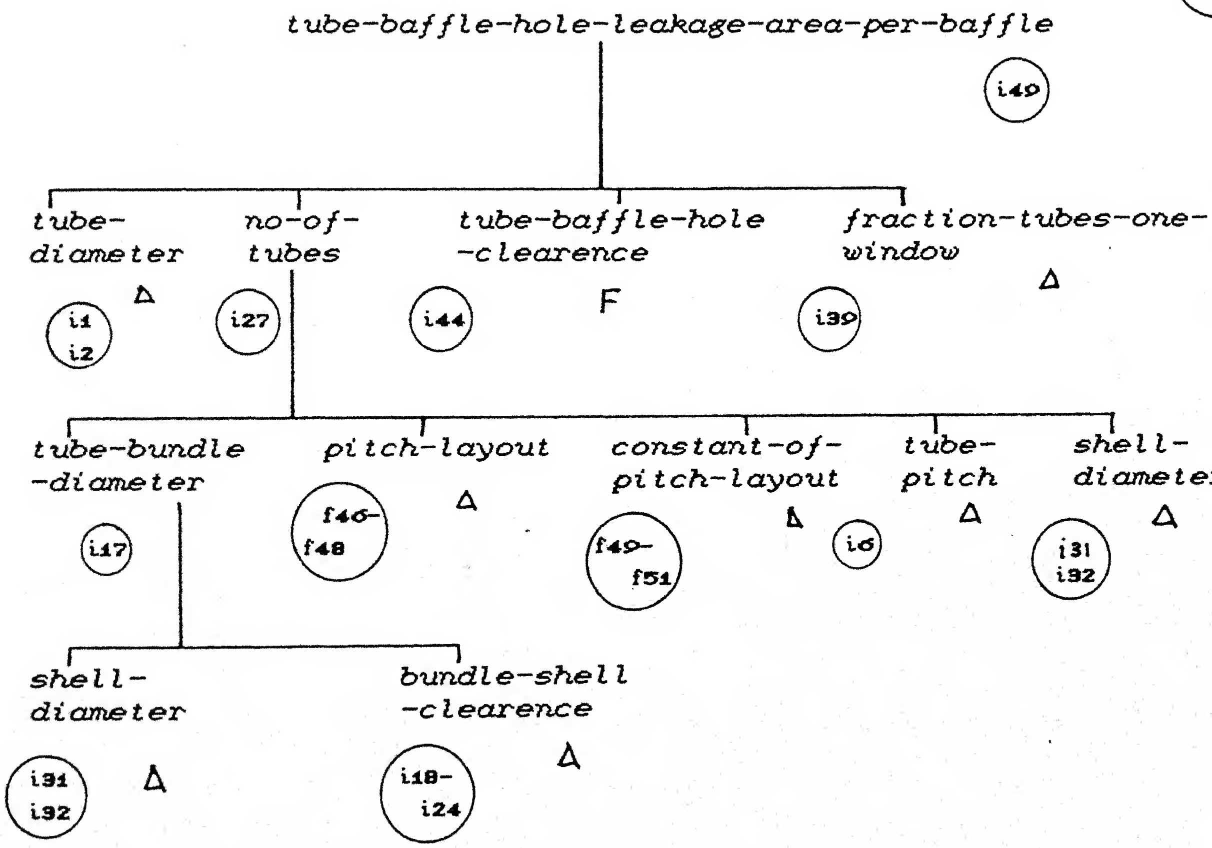

area-*
i5
pitch-layout
f46,f47
f48
constant-of-pitch-layout
f49,f50
f51
F
tube-diameter
i1
Q
i2
F
tube-pitch
i6
tube-diameter
Δ
i1,i2
pressure-drop
-strict
f45
Q
mechanical-cleaning
-frequent
f44
Q
retract-
all
Δ
bundle-diameter
i37
shell-diameter
i31
i32
Δ
bundle-shell-clearence
i18-i24
shell-diameter
i31
i32
Δ
bundle-type
f57-
f62
shell-side-fluid
c3
c4
inlet-pressure
f31
Q
bundle-type
f57
tube-side-fluid
c5,c6
fouling
f13
Q
inlet-pressure
f31
Δ
retract-all
Δ
bundle-type
f58
slightyly-greater-diameter
f20
Q
retract-all
Δ
bundle-type
f59
shell-side-fluid
c3
c4
Δ
inlet-pressure
f13
Δ
inlet-temp
f10
f11
Δ
cleaning-of-tubes
-insitu
Q
f18
retract-all
Δ

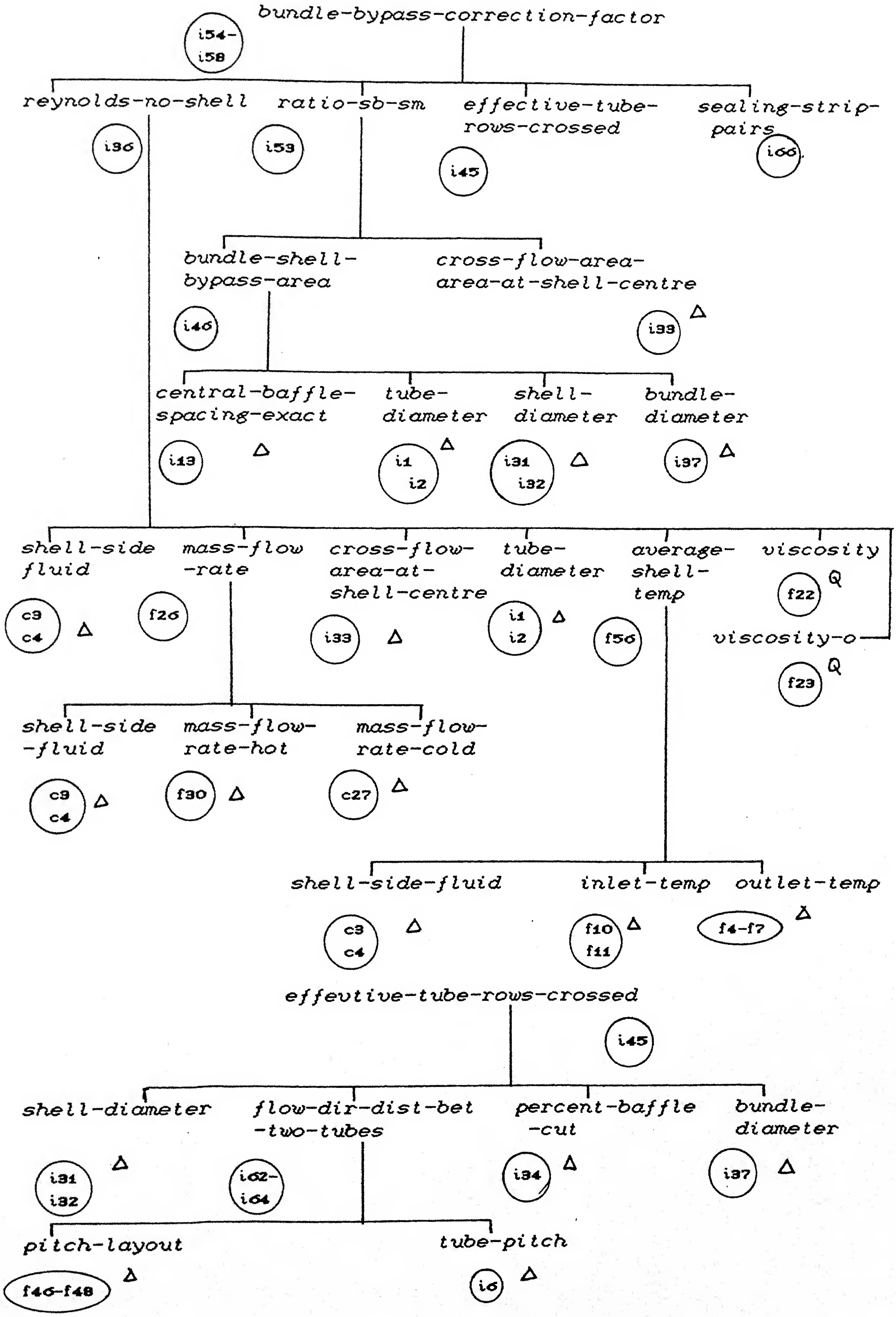


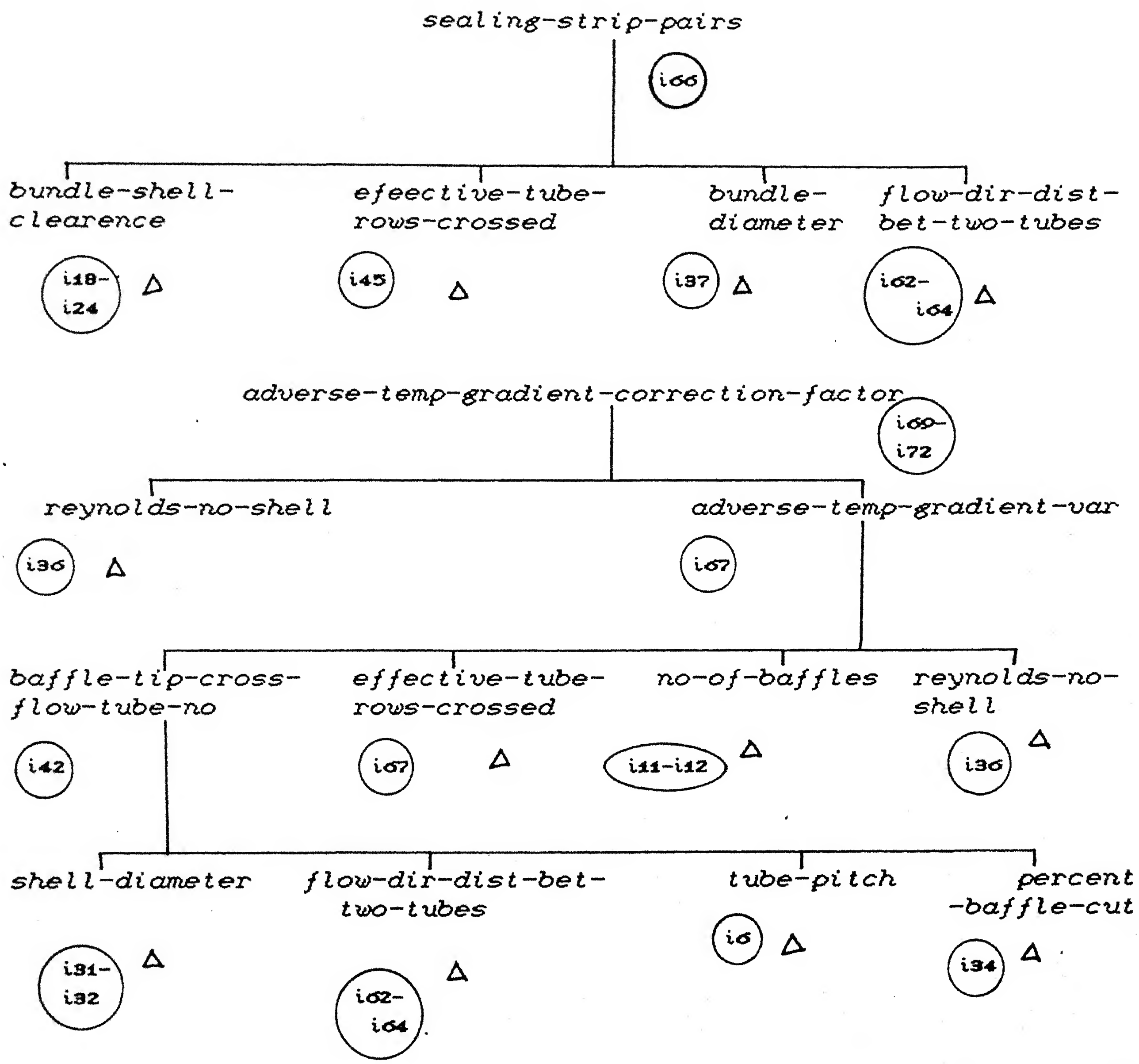
bundle-type
f60
shell-side-fluid
non-lethal
inlet-temp
inlet-pressure
c3,c4
f17
Q
f10
f11
Q
f31
retract-all
bundle-type
f61
shell-side-fluid
fouling
slight-leakage
retract-all
f19
Q
Q
c3
c4
f16
bundle-type
f62
retract-all
percent-baffle-cut
i34
central-baffle-spacing-exact
shell-diameter
i13
i31
i32
no-of-baffles
tube-length
shell-series
i11
i12
i29
i31
i32
Q
tube-length
central-baffle-spacing-approx
shell-series
i29
i15
f1
shell-diameter
i31
i32
shell-length
tube-sheet-thickness
fluid-name
inlet-temp
outlet-temp
i28
i16
shell-diameter
f12,c2
f10,f11
f4
-f7
i31
i32
s-series
shell-diameter
aspect-ratio
i25
i31
i32

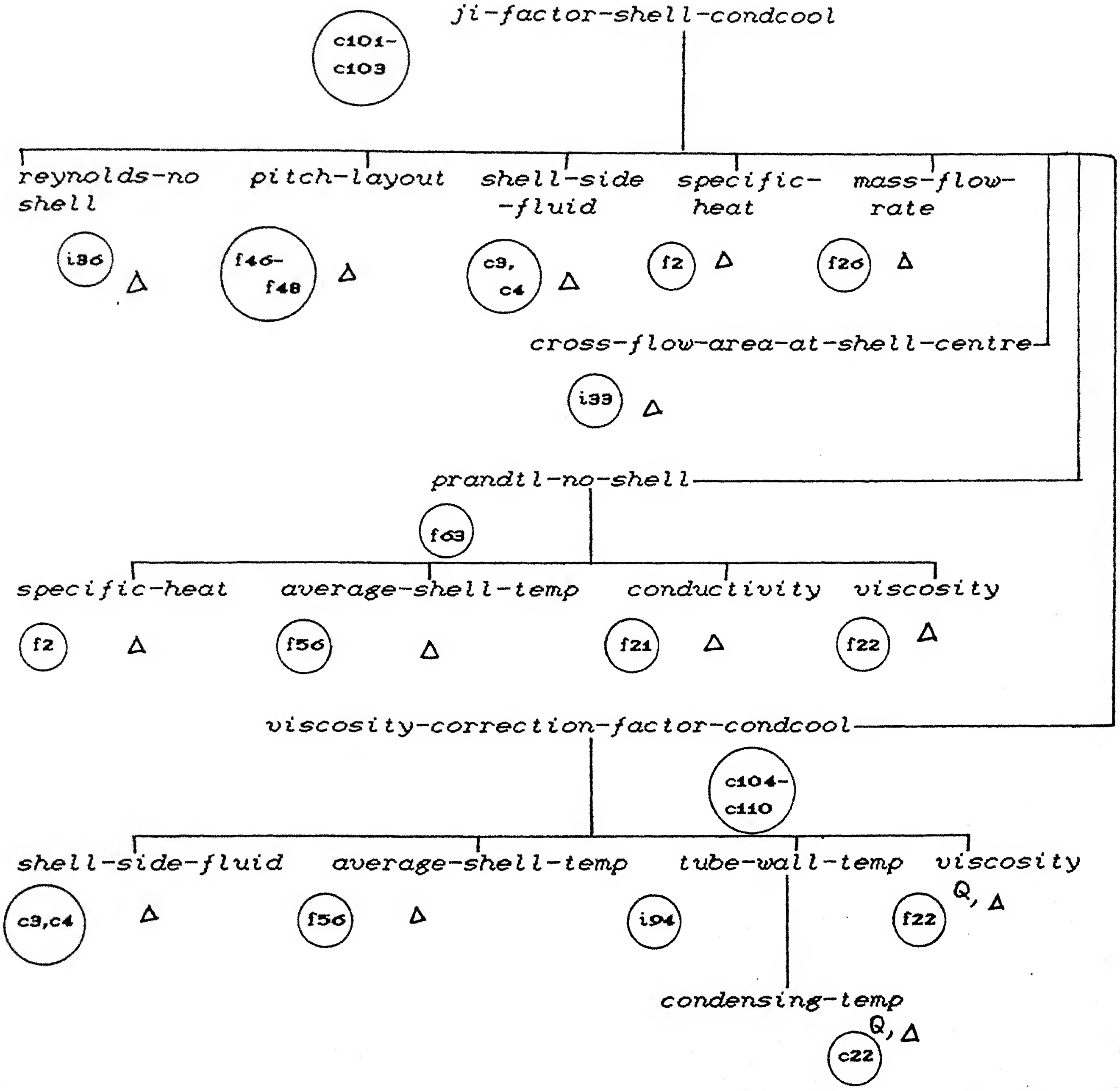

cross-flow-area-at-shell-centre
i93
central-baffle-spacing-exact
i13
bundle-shell-clearence
i18-i24
bundle-diameter
i37
tube-pitch
i6
tube-diameter
i1,i2
eff-constant-of-pitch-layout
f52-f54
shell-series
shell-side-fluid
c3
c4
cond-type
r9-r17
condensing-fluid
Q
c1
cond-type
r9-r17
fluid-name
f12


baffle-leakage-correction-factor
i51
shell-baffle-leakage -area
i48
tube-baffle-hole-leakage -area-per-baffle
i49
cross-flow-area -at-shell-centre
i33
shell-baffle-clearence
i65
shell-diameter
i31 i32
centriangle-of- baffle-cut
i35
percent-baffle-cut
i34
central-baffle- spacing-exact
i13
bundle-shell -clearence
i18-i24
i37
bundle- diameter
tube- pitch
i6
tube- diameter
i1 i2
effective -constant -of- pitch-layout
f52- f54
shell-diameter
i31 i32
bundle-shell -clearence
i18- i24
tube- pitch
i6
pitch- layout
f46- f48

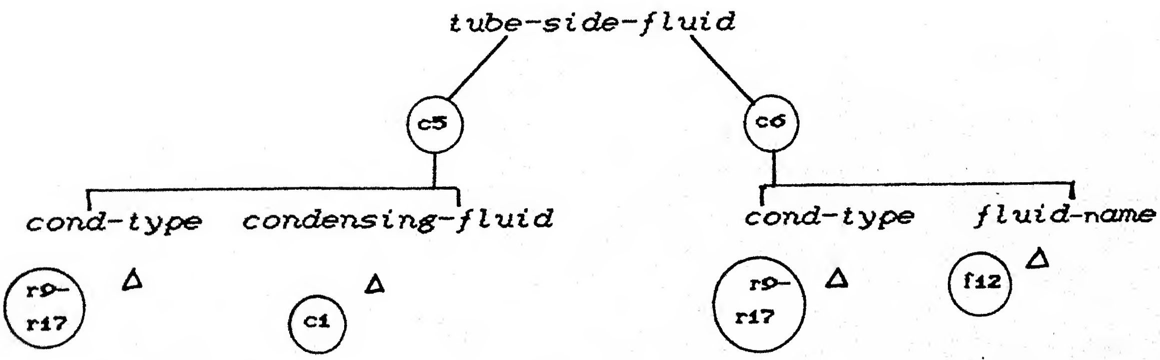

tube-baffle-hole-leakage-area-per-baffle
i49
tube- diameter
i1 i2
no-of- tubes
i27
tube-baffle-hole -clearence
i44
F
fraction-tubes-one- window
i39
tube-bundle -diameter
i17
pitch-layout
f46- f48
constant-of- pitch-layout
f49- f51
tube- pitch
i6
shell- diameter
i31 i32
shell- diameter
i31 i32
bundle-shell -clearence
i18- i24


bundle-bypass-correction-factor
i54-
i58
reynolds-no-shell
i36
ratio-sb-sm
i53
effective-tube-
rows-crossed
i45
sealing-strip-
pairs
i66
bundle-shell-
bypass-area
i46
cross-flow-area-
area-at-shell-centre
i33
central-baffle-
spacing-exact
i13
tube-
diameter
i1
i2
shell-
diameter
i31
i32
bundle-
diameter
i37
shell-side
fluid
c3
c4
mass-flow
-rate
f26
cross-flow-
area-at-
shell-centre
i33
tube-
diameter
i1
i2
average-
shell-
temp
f56
viscosity
f22
Q
viscosity-o
f23
Q
shell-side
-fluid
c3
c4
mass-flow-
rate-hot
f30
mass-flow-
rate-cold
c27
shell-side-fluid
c3
c4
inlet-temp
f10
f11
outlet-temp
f4-f7
effevtive-tube-rows-crossed
i45
shell-diameter
i31
i32
flow-dir-dist-bet
-two-tubes
i62-
i64
percent-baffle
-cut
i34
bundle-
diameter
i37
pitch-layout
f46-f48
tube-pitch
i6

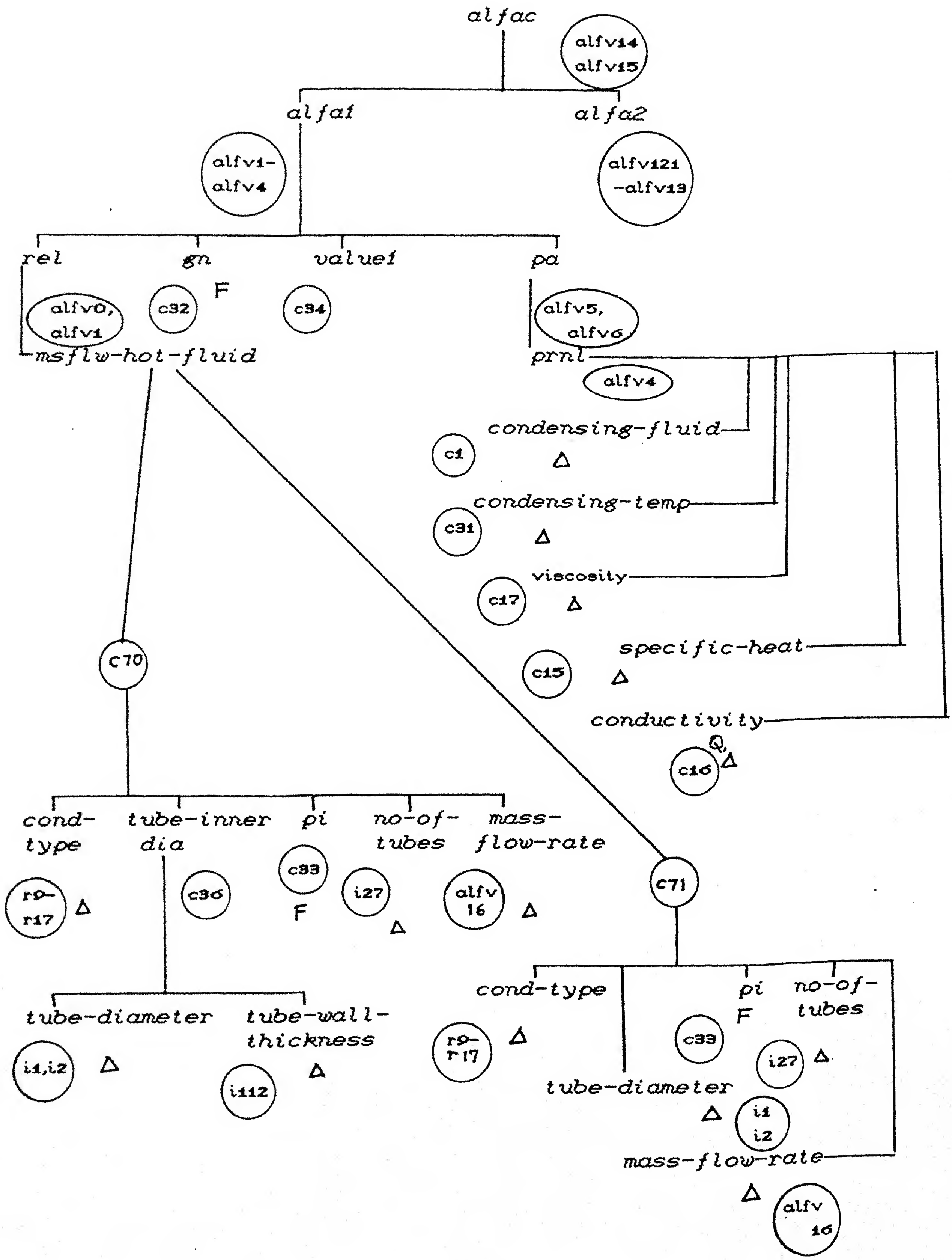

sealing-strip-pairs
i66
bundle-shell-clearence
i18-i24
efeective-tube-rows-crossed
i45
bundle-diameter
i37
flow-dir-dist-bet-two-tubes
i62-i64
adverse-temp-gradient-correction-factor
i69-i72
reynolds-no-shell
i36
adverse-temp-gradient-var
i67
baffle-tip-cross-flow-tube-no
i42
effective-tube-rows-crossed
i67
no-of-baffles
i11-i12
reynolds-no-shell
i36
shell-diameter
i31-i32
flow-dir-dist-bet-two-tubes
i62-i64
tube-pitch
i6
percent-baffle-cut
i34

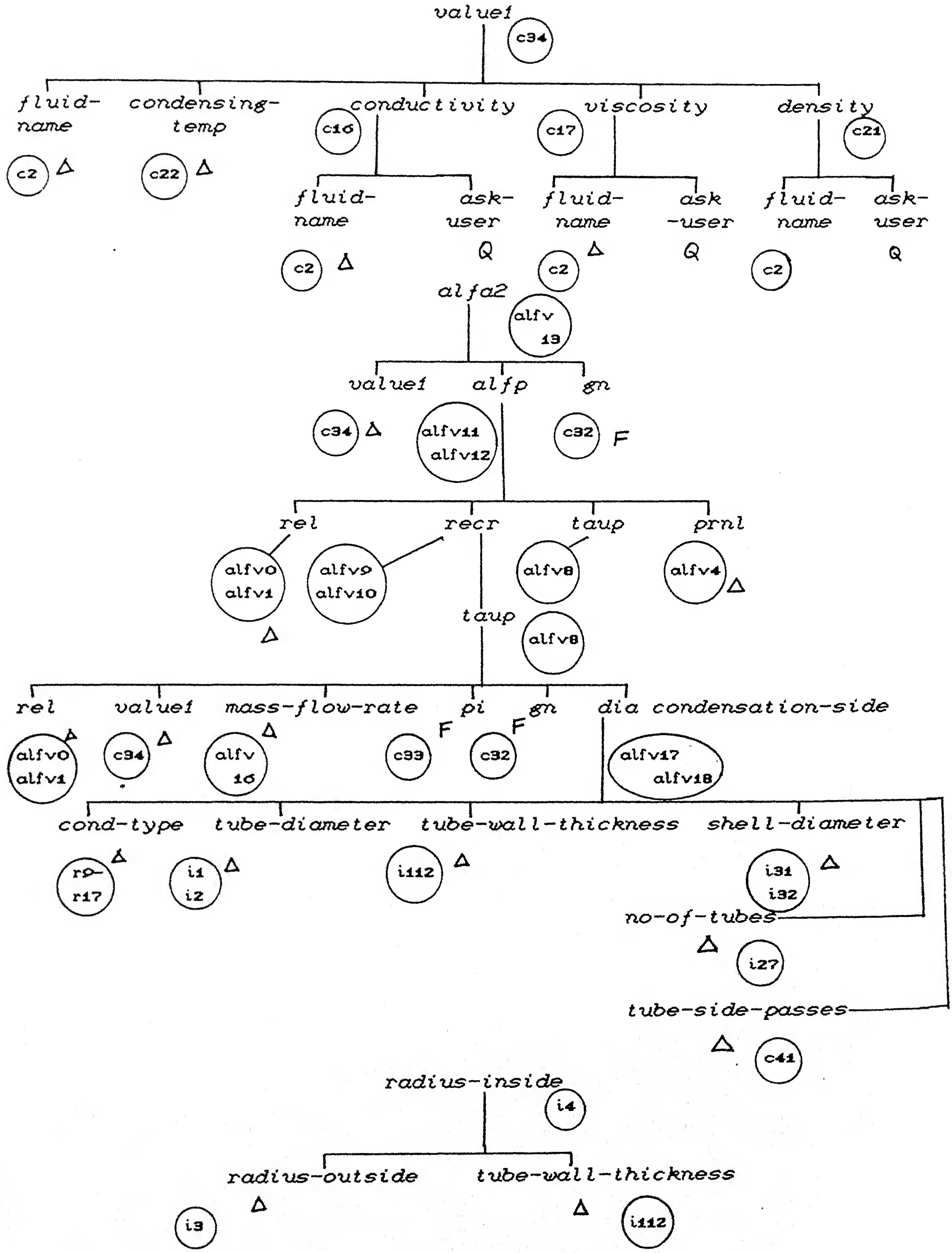


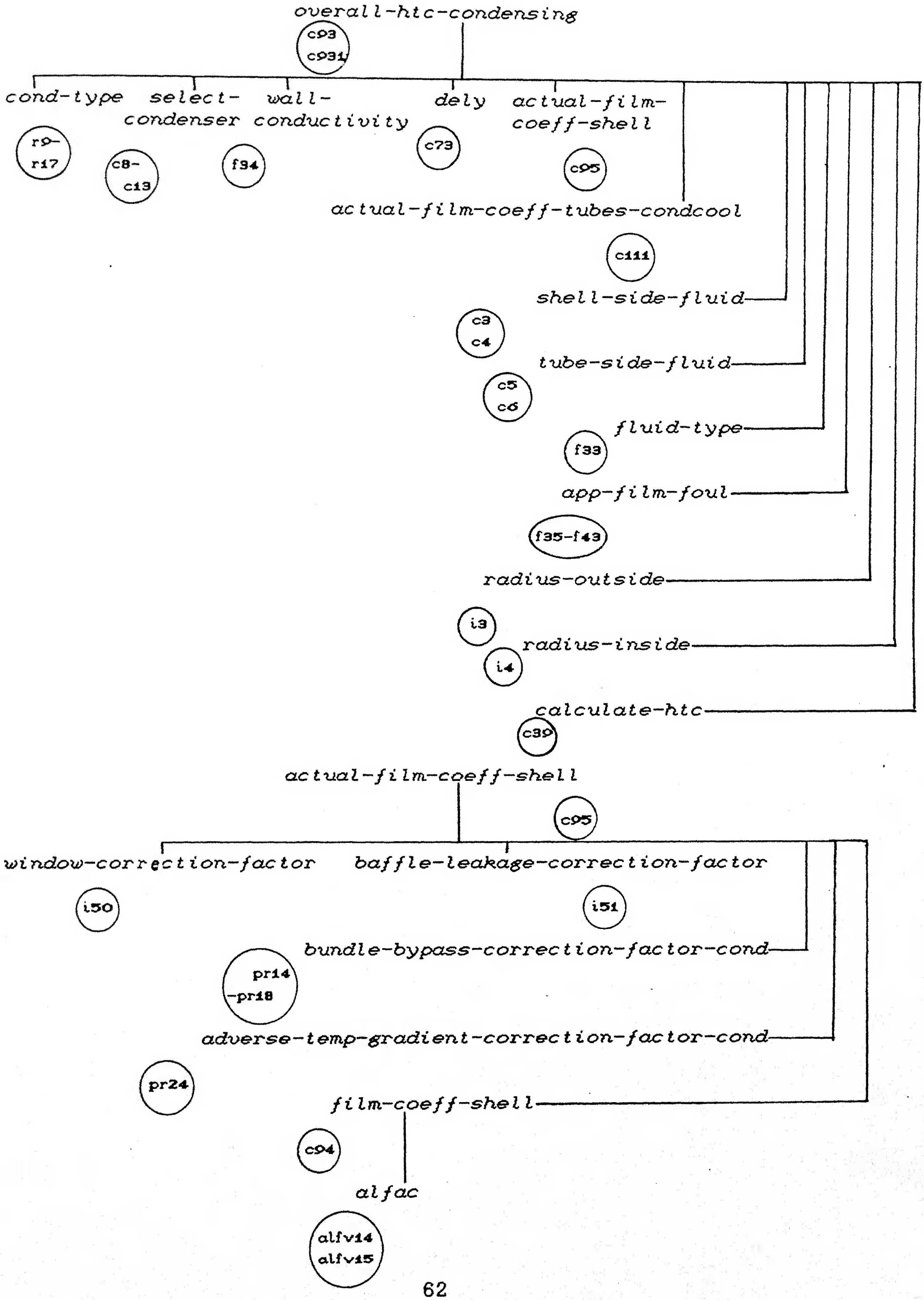
ji-factor-shell-condcool
c101-c103
reynolds-no shell
i36
pitch-layout
f46-f48
shell-side-fluid
c3, c4
specific-heat
f2
mass-flow-rate
f26
cross-flow-area-at-shell-centre
i33
prandtl-no-shell
f63
specific-heat
f2
average-shell-temp
f56
conductivity
f21
viscosity
f22
viscosity-correction-factor-condcool
c104-c110
shell-side-fluid
c3,c4
average-shell-temp
f56
tube-wall-temp
i94
viscosity
Q,
f22
condensing-temp
Q,
c22



tube-side-fluid
c5
c6
cond-type
r9-r17
condensing-fluid
c1
cond-type
r9-r17
fluid-name
f12


alfac
alfv14
alfv15
alfa1
alfa2
alfv1-
alfv4
alfv121
-alfv13
rel
gn
value1
pa
F
alfv0,
alfv1
c32
c34
alfv5,
alfv6
msflw-hot-fluid
prnl
alfv4
condensing-fluid
c1
condensing-temp
c31
viscosity
c17
specific-heat
c15
conductivity
Q
c16
c70
cond-
type
tube-inner
dia
pi
no-of-
tubes
mass-
flow-rate
c33
F
r9-
r17
c36
i27
alfv
16
c71
tube-diameter
tube-wall-
thickness
i1,i2
i112
cond-type
pi
no-of-
tubes
F
c33
r9-
r17
i27
tube-diameter
i1
i2
mass-flow-rate
alfv
16


value1
c34
fluid-name
c2
condensing-temp
c22
conductivity
c16
fluid-name
c2
ask-user
Q
viscosity
c17
fluid-name
c2
ask-user
Q
density
c21
fluid-name
c2
ask-user
Q
alfa2
alfv13
value1
c34
alfp
alfv11 alfv12
gn
c32
F
rel
alfv0 alfv1
recr
alfv9 alfv10
taup
alfv8
prnl
alfv4
taup
alfv8
rel
alfv0 alfv1
value1
c34
mass-flow-rate
alfv16
pi
c33
F
gn
c32
F
dia
condensation-side
alfv17 alfv18
cond-type
r9-r17
tube-diameter
i1 i2
tube-wall-thickness
i112
shell-diameter
i31 i32
no-of-tubes
i27
tube-side-passes
c41
radius-inside
i4
radius-outside
i3
tube-wall-thickness
i112


overall-htc-condensing
c93
c931
cond-type
r9-
r17
select-
condenser
c8-
c13
wall-
conductivity
f34
dely
c73
actual-film-
coeff-shell
c95
actual-film-coeff-tubes-condcool
c111
shell-side-fluid
c3
c4
tube-side-fluid
c5
c6
fluid-type
f33
app-film-foul
f35-f43
radius-outside
i3
radius-inside
i4
calculate-htc
c39
actual-film-coeff-shell
c95
window-correction-factor
i50
baffle-leakage-correction-factor
i51
bundle-bypass-correction-factor-cond
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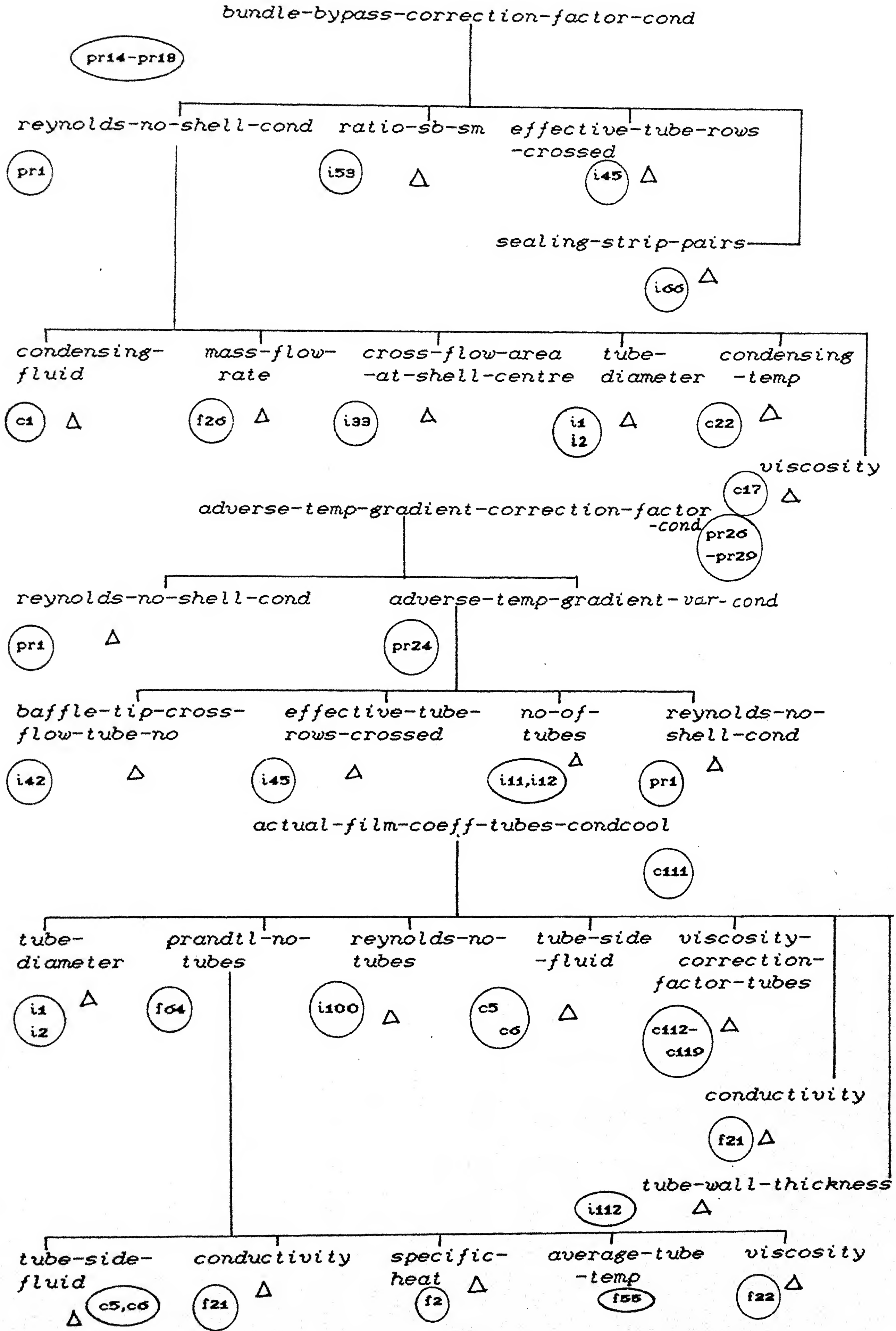
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i66
condensing-
fluid
c1
mass-flow-
rate
f26
cross-flow-area
-at-shell-centre
i33
tube-
diameter
i1
i2
condensing
-temp
c22
viscosity
c17
adverse-temp-gradient-correction-factor
-cond
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-pr29
reynolds-no-shell-cond
pr1
adverse-temp-gradient-var-cond
pr24
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flow-tube-no
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effective-tube-
rows-crossed
i45
no-of-
tubes
i11,i12
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shell-cond
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diameter
i1
i2
prandtl-no-
tubes
f64
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tubes
i100
tube-side
-fluid
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c6
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correction-
factor-tubes
c112-
c119
conductivity
f21
tube-wall-thickness
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specific-
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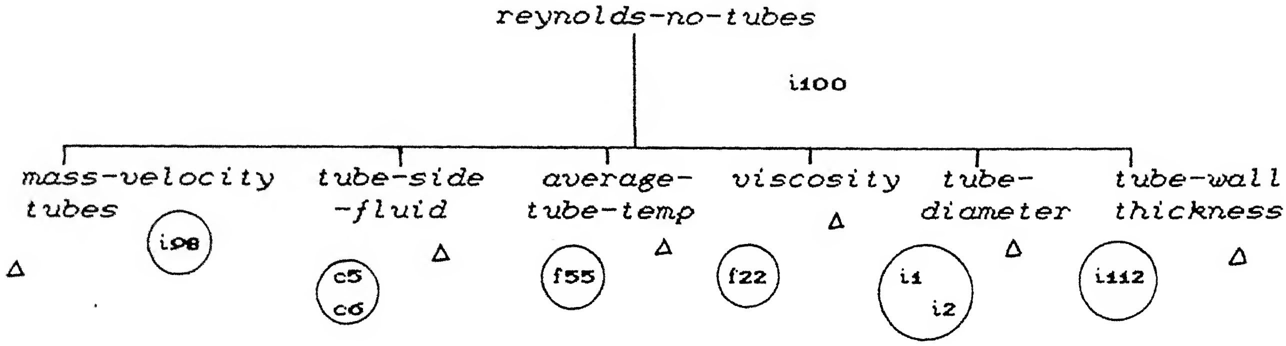
viscosity
f22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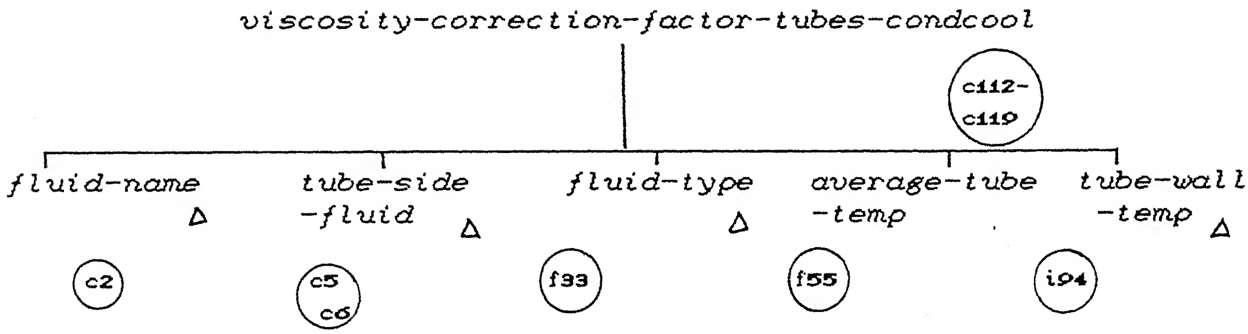
i1 i2
tube-wall thickness
i112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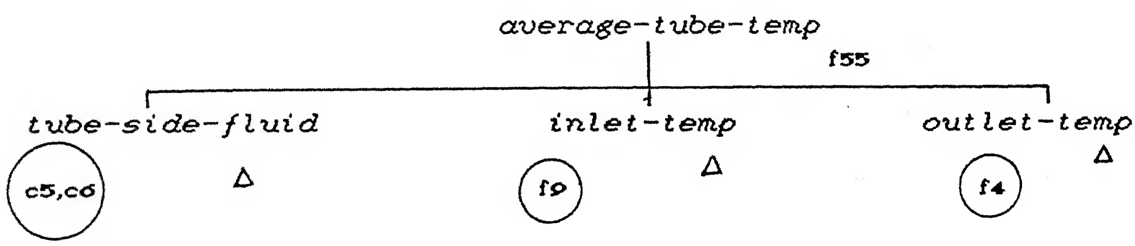
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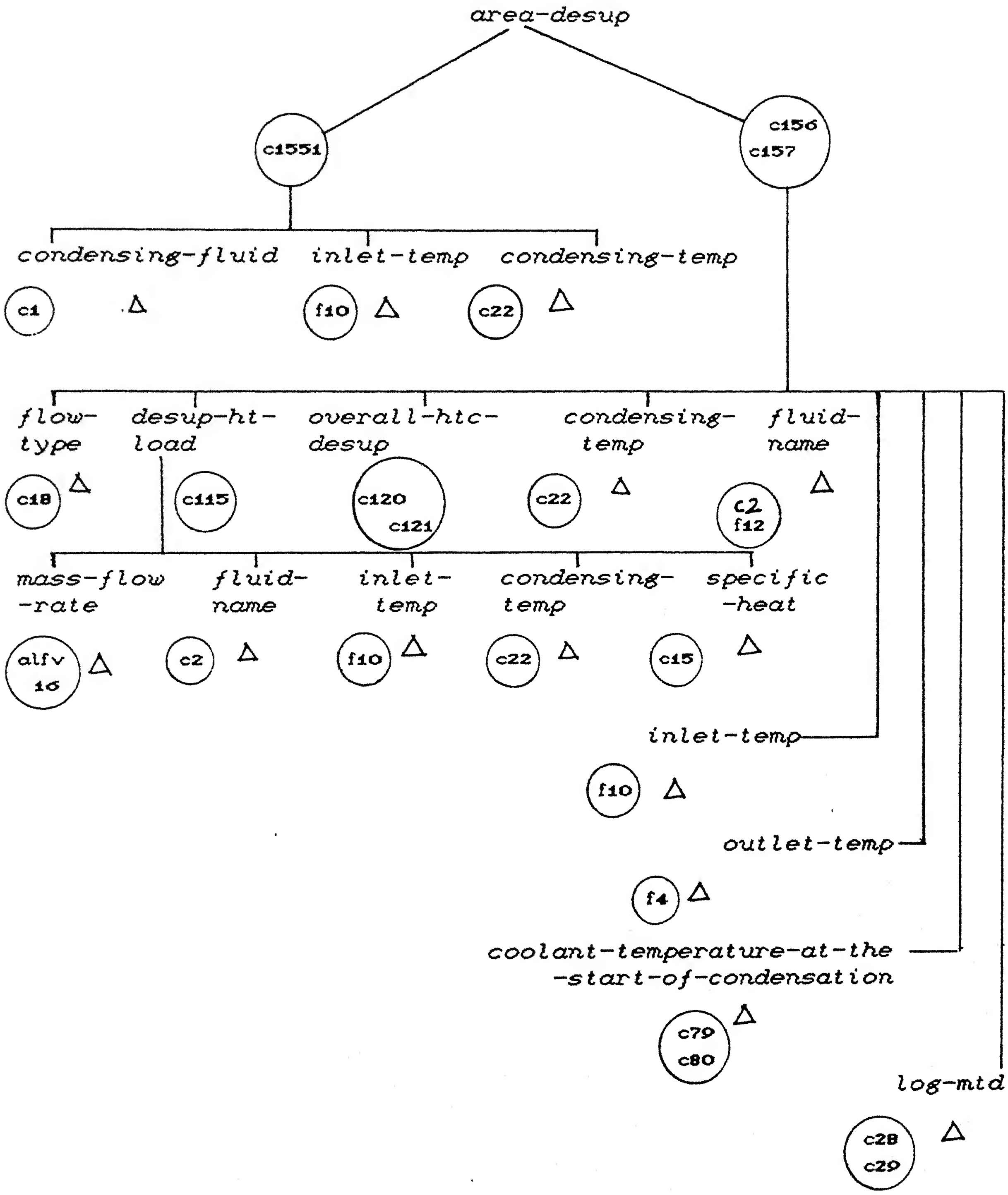
outlet-temp
f4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c157
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condensing-temp
c1
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c22
flow-type
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overall-htc-desup
condensing-temp
fluid-name
c18
c115
c120
c121
c22
c2
f12
mass-flow-rate
fluid-name
inlet-temp
condensing-temp
specific-heat
alfv
16
c2
f10
c22
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f10
outlet-temp
f4
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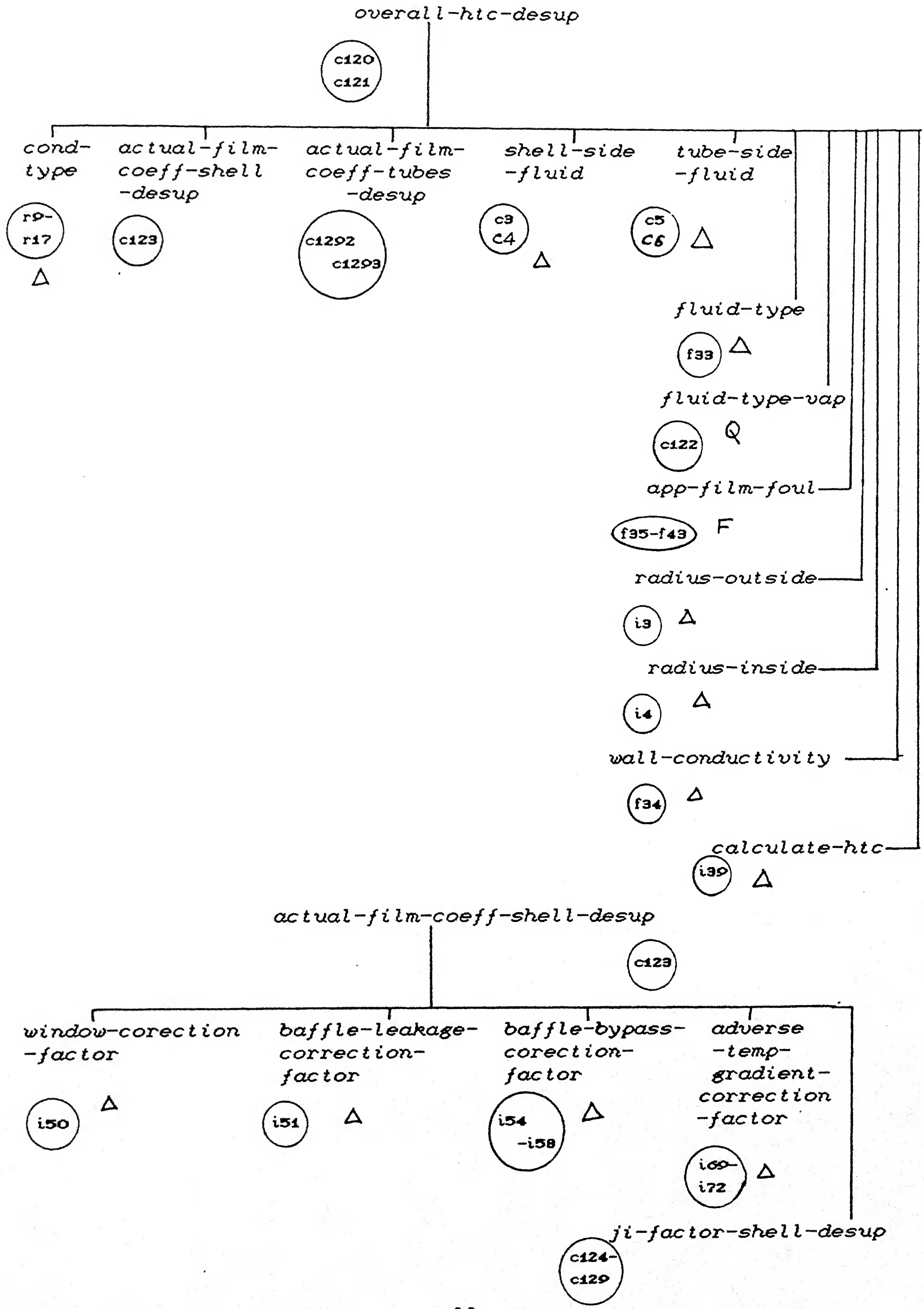
c80
log-mtd
c28
c29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c1293
shell-side-fluid
c3
c4
tube-side-fluid
c5
c6
fluid-type
f33
fluid-type-vap
c122
Q
app-film-foul
f35-f43
F
radius-outside
i3
radius-inside
i4
wall-conductivity
f34
calculate-htc
i39
actual-film-coeff-shell-desup
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window-corection-factor
i50
baffle-leakage-correction-factor
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baffle-bypass-corection-factor
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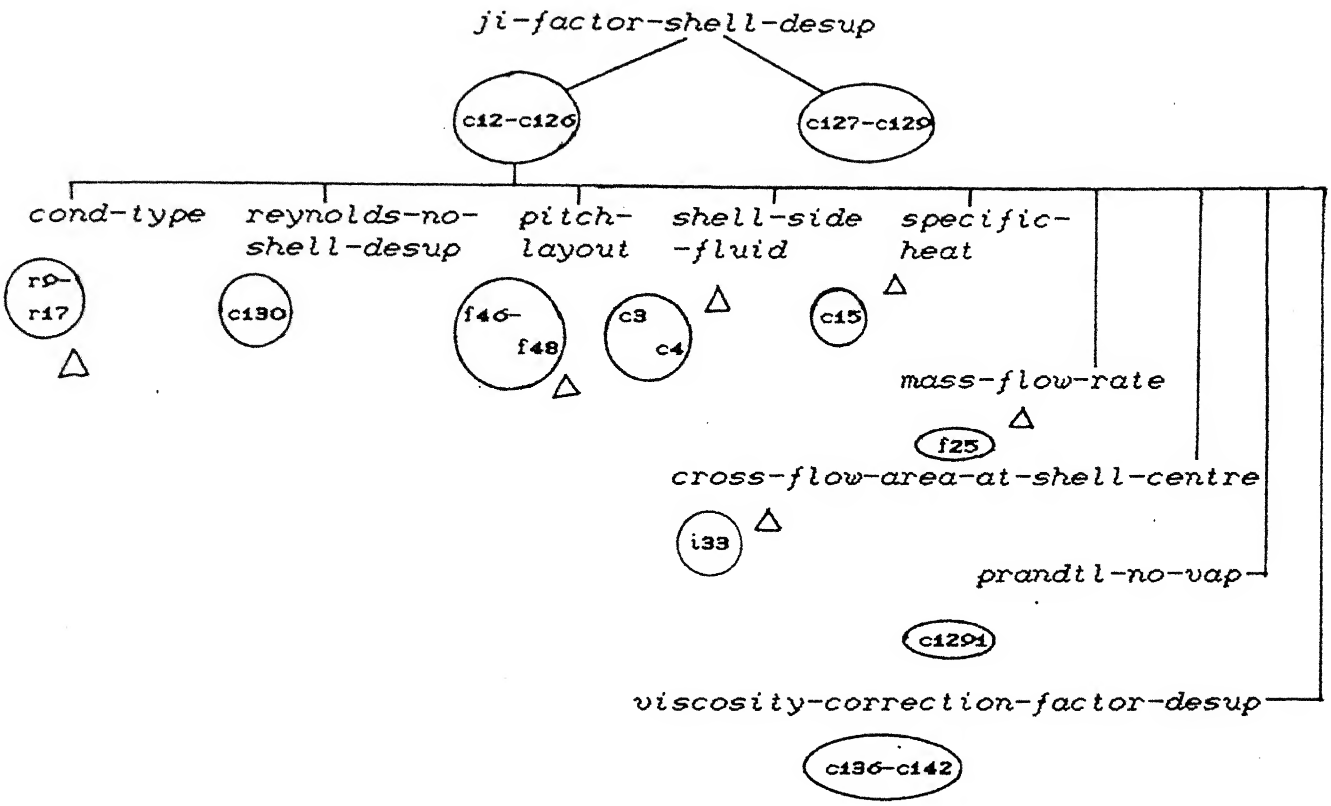
i69-i72
ji-factor-shell-desup
c124-c129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pitch-layout
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shell-side-fluid
c3 c4
specific-heat
c15
mass-flow-rate
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prandtl-no-vap
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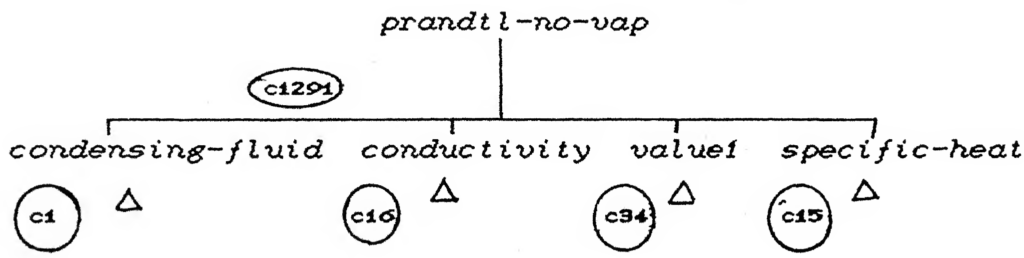
viscosity-correction-factor-desup
c136-c142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conductivity
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value1
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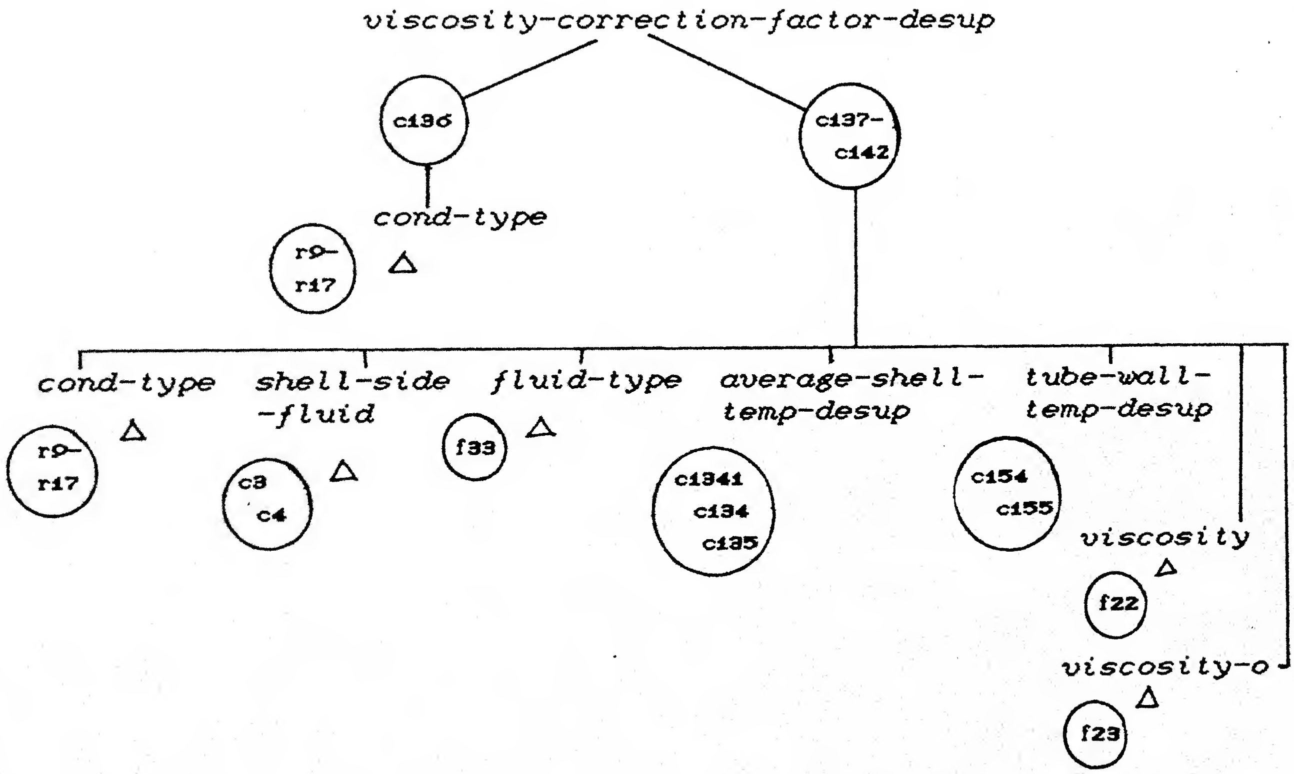
specific-heat
c15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c137-c142
cond-type
r9-r17
cond-type
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fluid-type
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tube-wall-temp-desup
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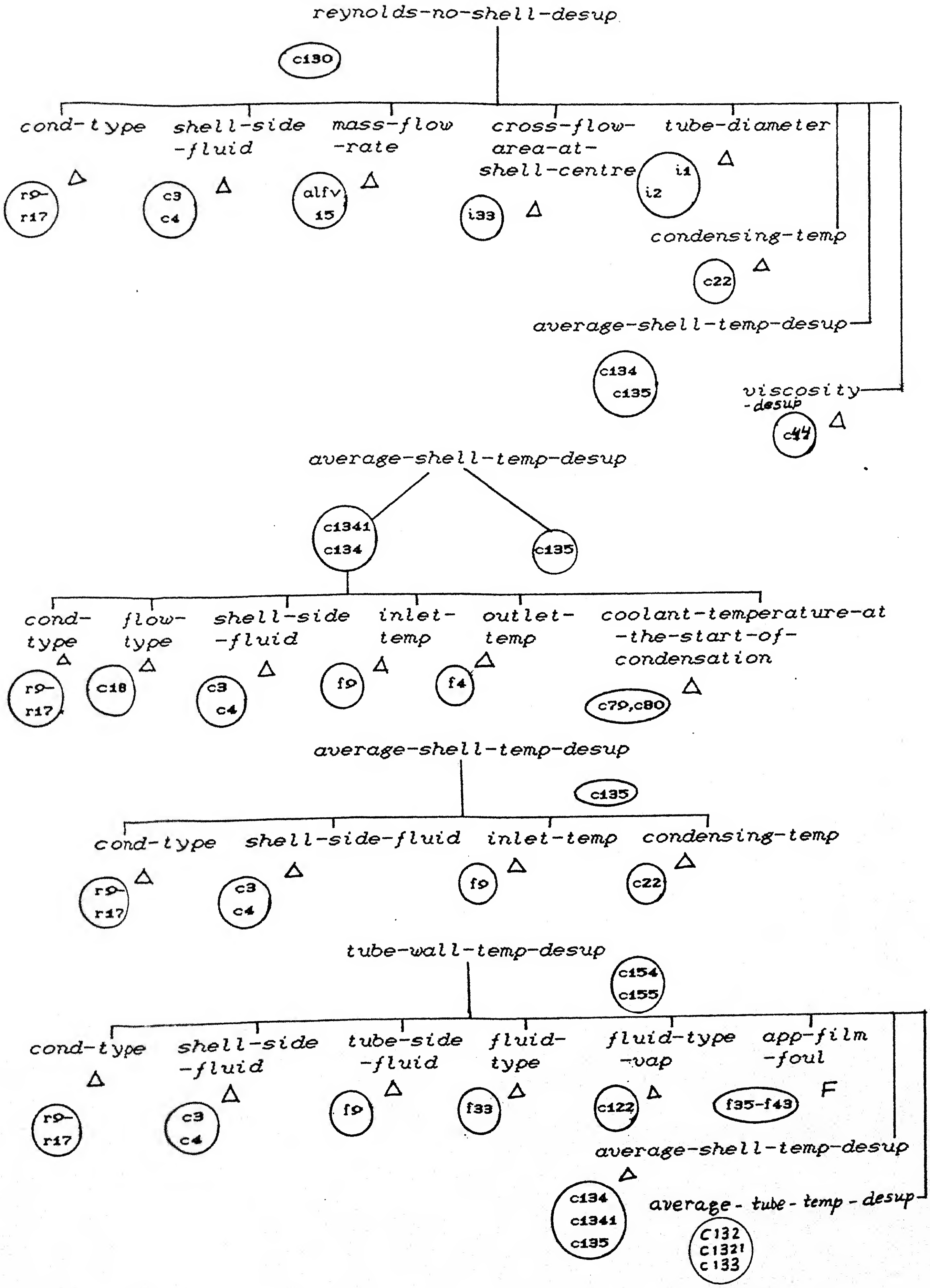
viscosity
f22
viscosity-o
f23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mass-flow-rate
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i33
tube-diameter
i1 i2
condensing-temp
c22
average-shell-temp-desup
c134 c135
viscosity-desup
c44
average-shell-temp-desup
c1341 c134
c135
cond-type
r9-r17
flow-type
c18
shell-side-fluid
c3 c4
inlet-temp
f9
outlet-temp
f4
coolant-temperature-at-the-start-of-condensation
c79,c80
average-shell-temp-desup
c135
cond-type
r9-r17
shell-side-fluid
c3 c4
inlet-temp
f9
condensing-temp
c22
tube-wall-temp-desup
c154 c155
cond-type
r9-r17
shell-side-fluid
c3 c4
tube-side-fluid
f9
fluid-type
f33
fluid-type-vap
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f35-f43
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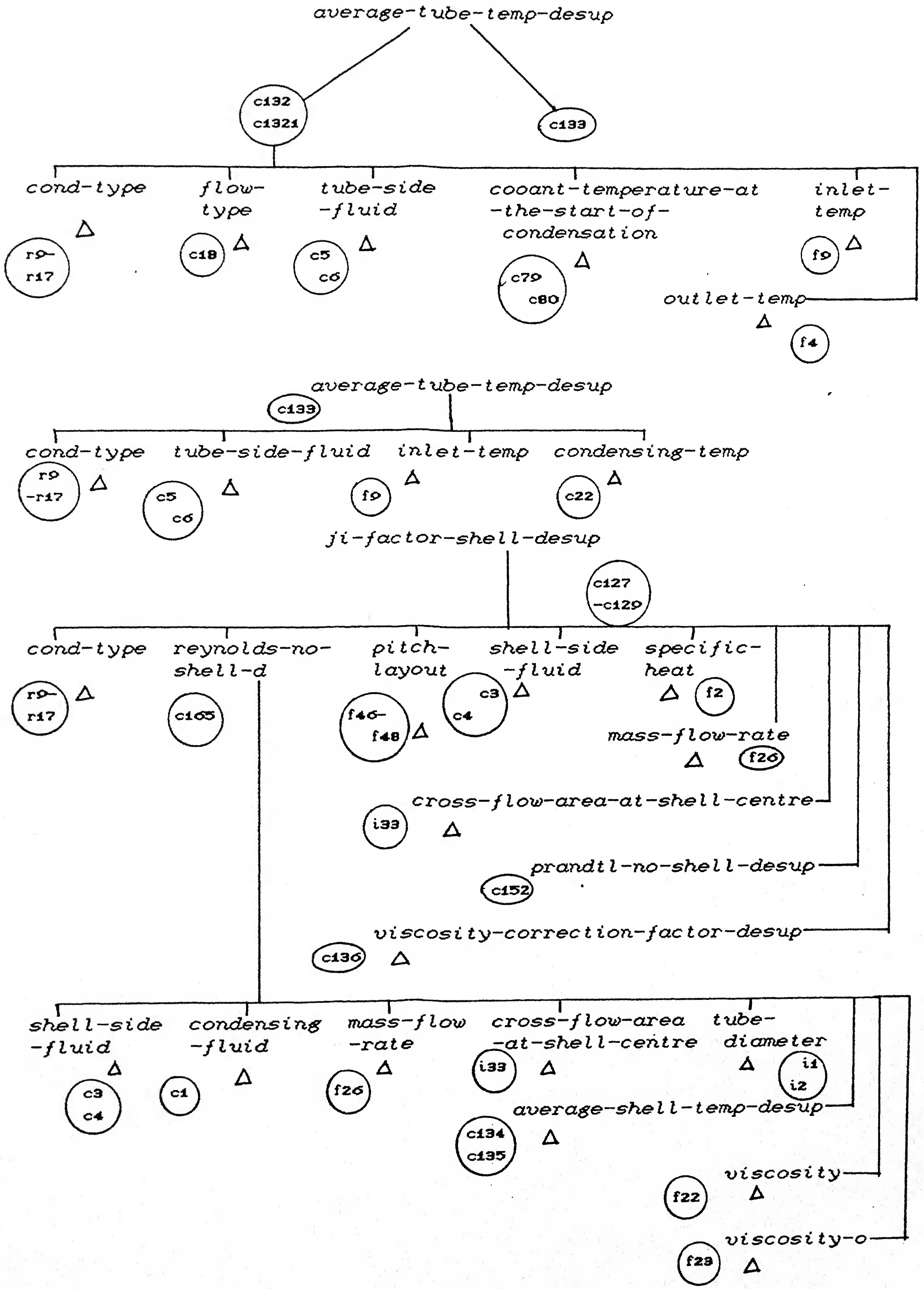
average-tube-temp-desup
c132 c1321 c133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c1321
c133
cond-type
r9-
r17
flow-
type
c18
tube-side
-fluid
c5
c6
cooant-temperature-at
-the-start-of-
condensation
c79
c80
inlet-
temp
f9
outlet-temp
f4
average-tube-temp-desup
c133
cond-type
r9
-r17
tube-side-fluid
c5
c6
inlet-temp
f9
condensing-temp
c22
ji-factor-shell-desup
c127
-c129
cond-type
r9-
r17
reynolds-no-
shell-d
c165
pitch-
layout
f46-
f48
shell-side
-fluid
c3
c4
specific-
heat
f2
mass-flow-rate
f26
cross-flow-area-at-shell-centre
i33
prandtl-no-shell-desup
c152
viscosity-correction-factor-desup
c136
shell-side
-fluid
c3
c4
condensing
-fluid
c1
mass-flow
-rate
f26
cross-flow-area
-at-shell-centre
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tube-
diameter
i1
i2
average-shell-temp-desup
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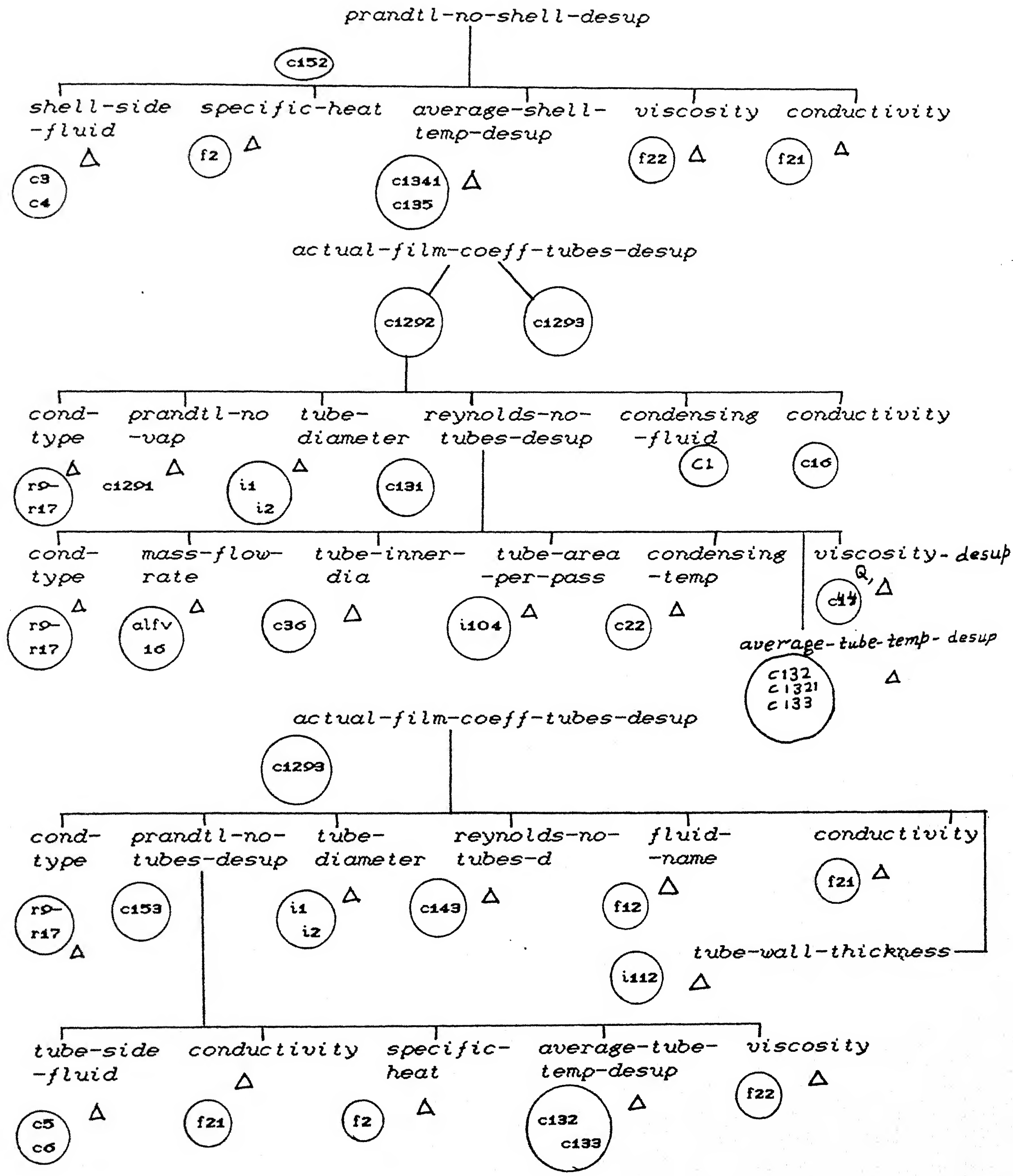
c135
viscosity
f22
viscosity-o
f23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shell-side -fluid
c3 c4
specific-heat
f2
average-shell-temp-desup
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viscosity
f22
conductivity
f21
actual-film-coeff-tubes-desup
c1292
c1293
cond-type
r9-r17
prandtl-no -vap
c1291
tube-diameter
i1 i2
reynolds-no-tubes-desup
c131
condensing -fluid
C1
conductivity
c16
cond-type
r9-r17
mass-flow-rate
alfv 16
tube-inner-dia
c36
tube-area -per-pass
i104
condensing -temp
c22
viscosity-desup
average-tube-temp-desup
c132 c1321 c133
actual-film-coeff-tubes-desup
c1293
cond-type
r9-r17
prandtl-no-tubes-desup
c153
tube-diameter
i1 i2
reynolds-no-tubes-d
c143
fluid--name
f12
conductivity
f21
tube-wall-thickness
i112
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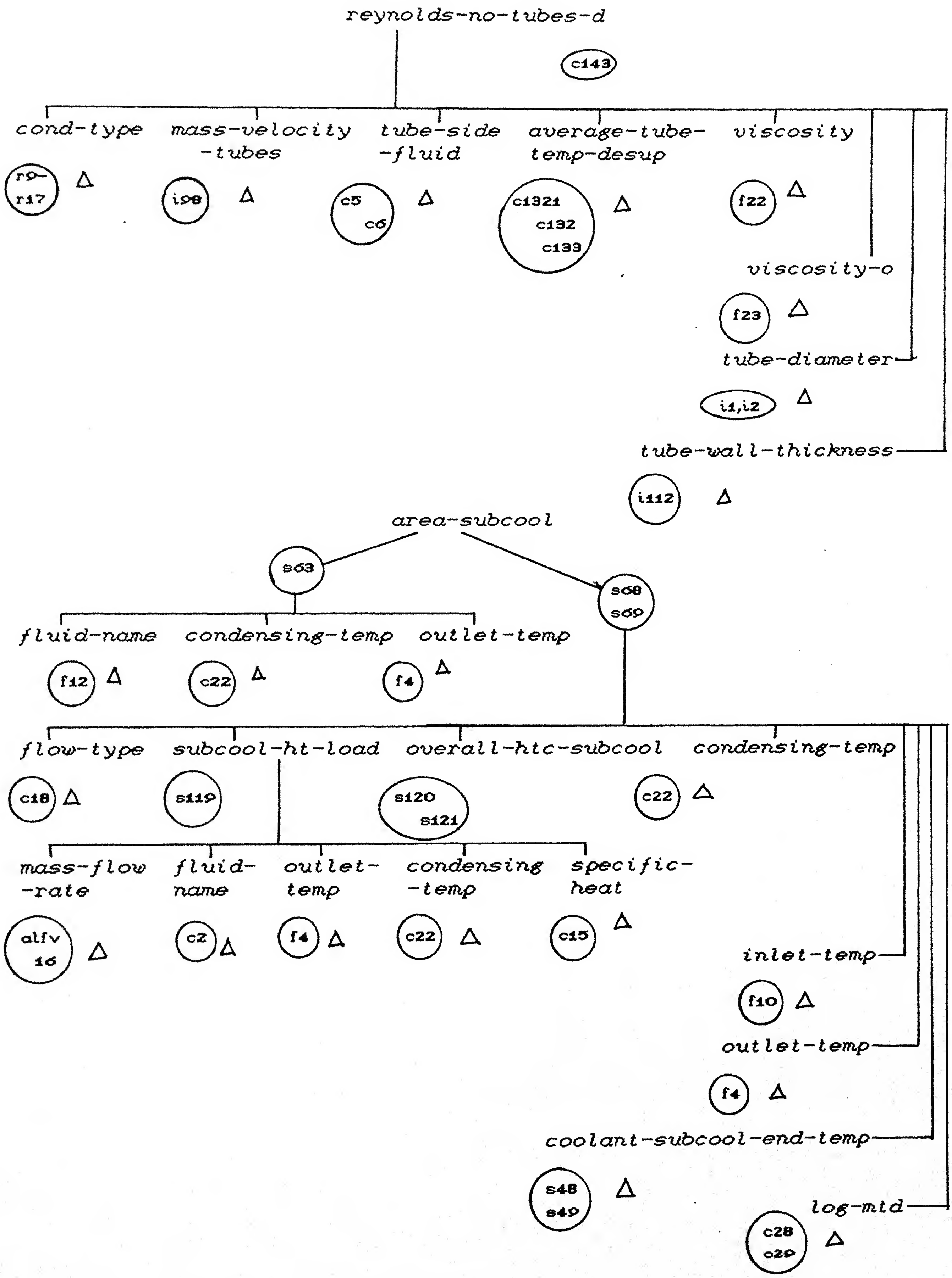
c5 c6
conductivity
f21
specific-heat
f2
average-tube-temp-desup
c132 c133
viscosity
f22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i98
tube-side -fluid
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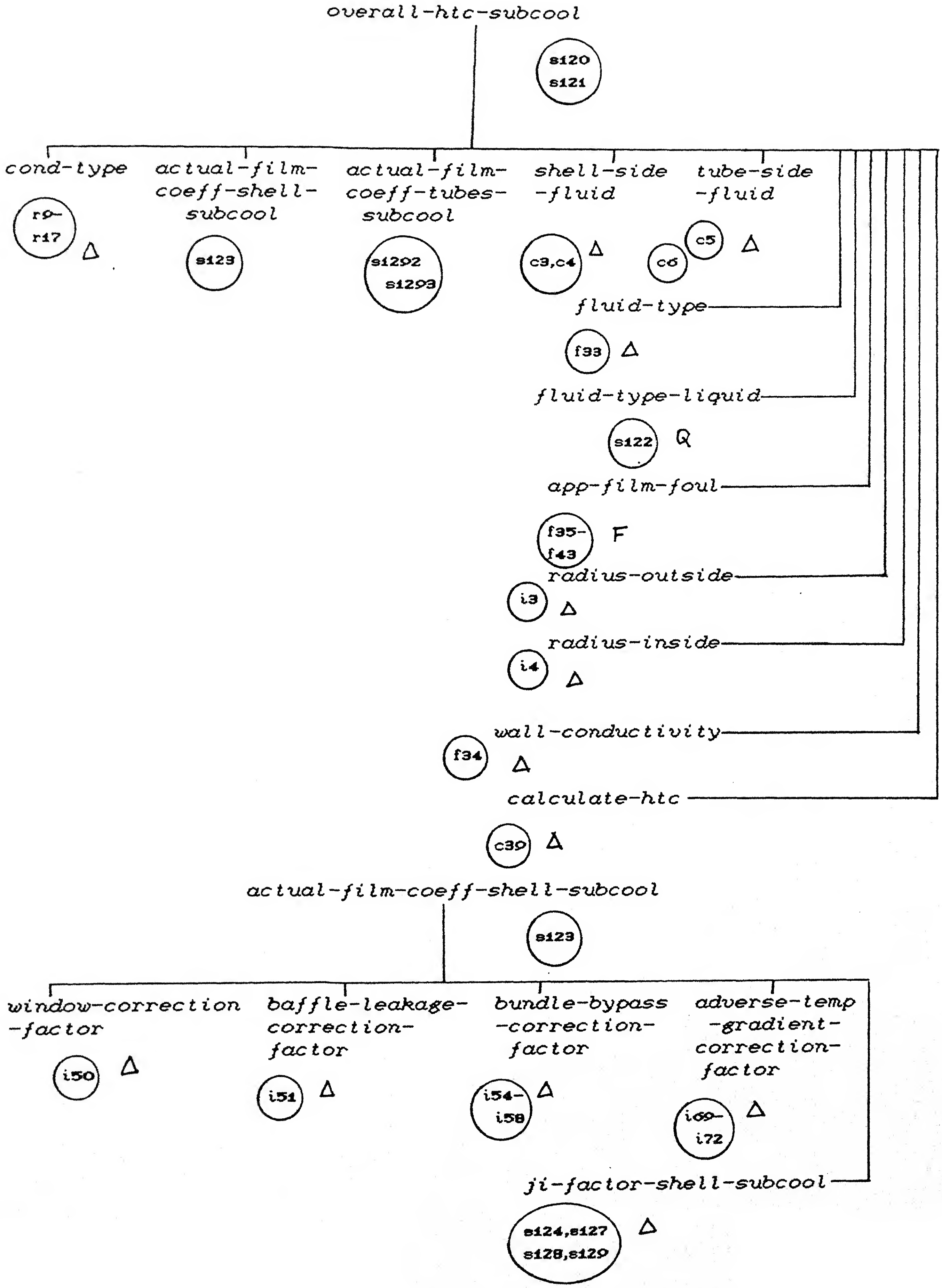
c1321 c132 c133
viscosity
f22
viscosity-o
f23
tube-diameter
i1,i2
tube-wall-thickness
i112
area-subcool
s63
s68 s69
fluid-name
f12
condensing-temp
c22
outlet-temp
f4
flow-type
c18
subcool-ht-load
s119
overall-htc-subcool
s120 s121
condensing-temp
c22
mass-flow -rate
alfv 16
fluid-name
c2
outlet-temp
f4
condensing -temp
c22
specific-heat
c15
inlet-temp
f10
outlet-temp
f4
coolant-subcool-end-temp
s48 s49
log-mtd
c28 c29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r17
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coeff-tubes-
subcool
s1292
s1293
shell-side
-fluid
c3,c4
tube-side
-fluid
c5
c6
fluid-type
f33
fluid-type-liquid
s122
Q
app-film-foul
f35-
f43
F
radius-outside
i3
radius-inside
i4
wall-conductivity
f34
calculate-htc
c39
actual-film-coeff-shell-subcool
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window-correction
-factor
i50
baffle-leakage-
correction-
factor
i51
bundle-bypass
-correction-
factor
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factor
i69-
i72
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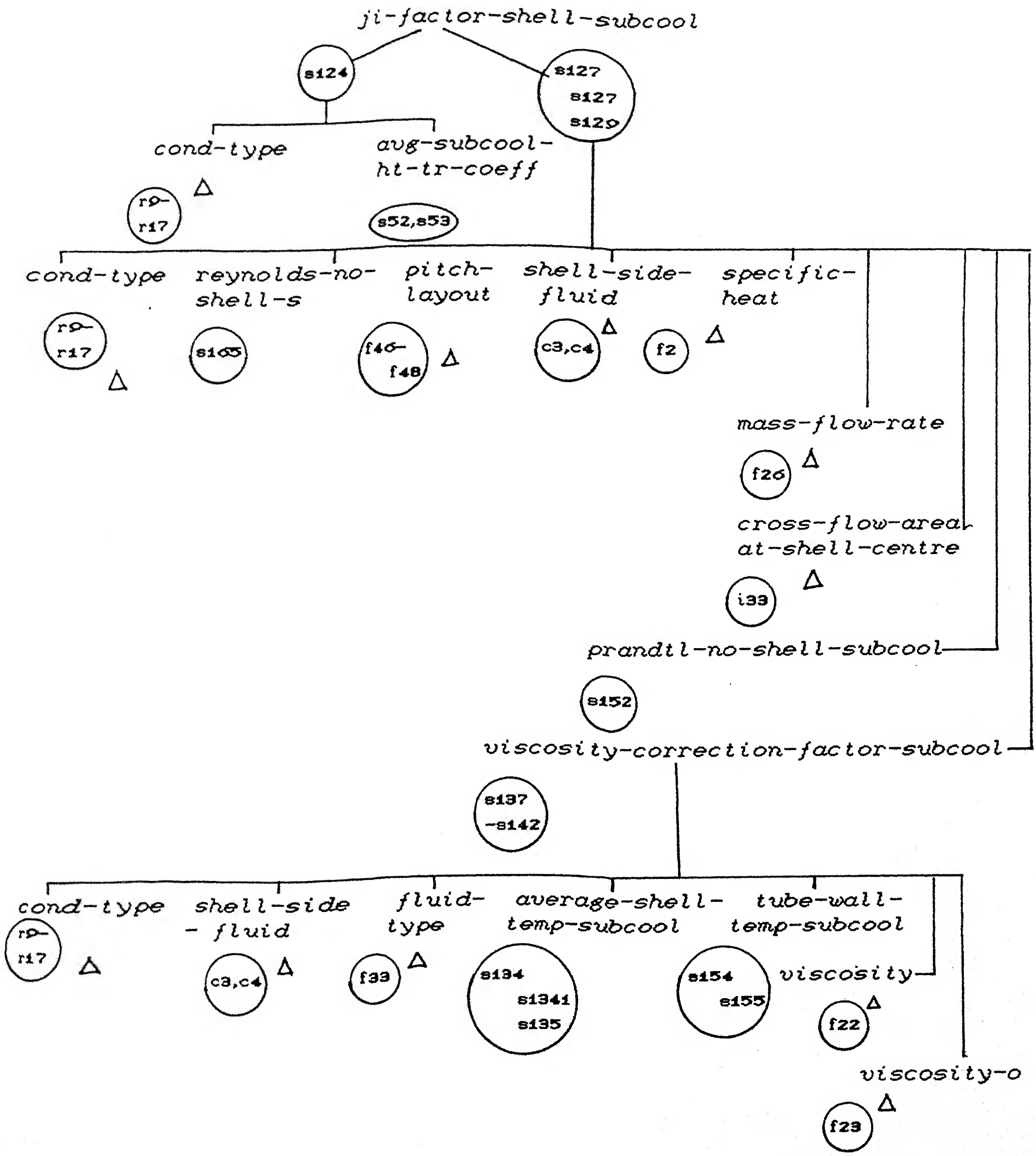
s128,s129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shell-s
pitch-
layout
shell-side-
fluid
specific-
heat
r9-
r17
s105
f46-
f48
c3,c4
f2
mass-flow-rate
f26
cross-flow-area
at-shell-centre
i33
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viscosity-correction-factor-subcool
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-s142
cond-type
shell-side
- fluid
fluid-
type
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temp-subcool
tube-wall-
temp-subcool
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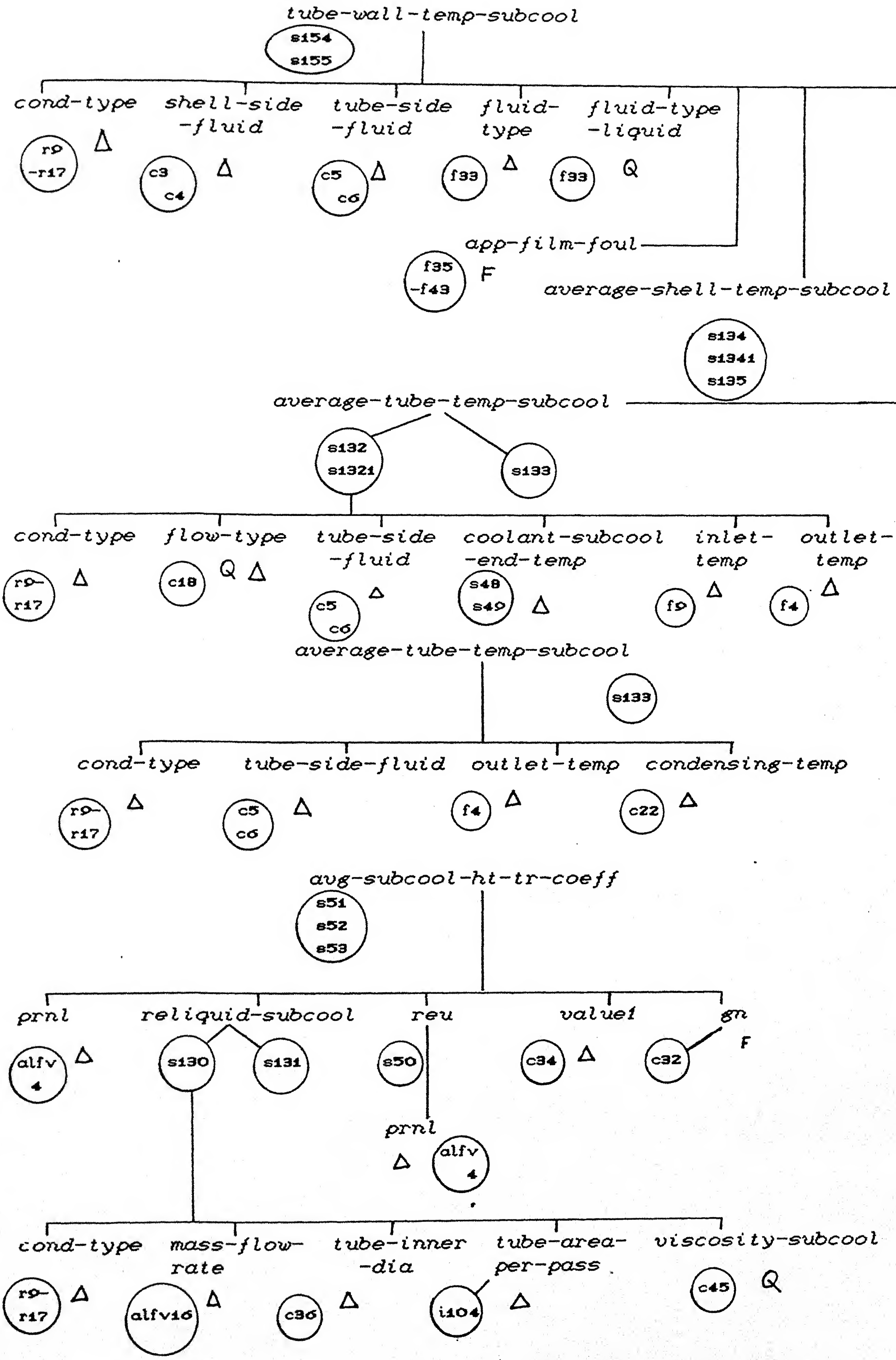
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c6
fluid-
type
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fluid-type
-liquid
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app-film-foul
f35
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F
average-shell-temp-subcool
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s1341
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average-tube-temp-subcool
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s1321
s133
cond-type
r9-
r17
flow-type
c18
Q
tube-side
-fluid
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c6
coolant-subcool
-end-temp
s48
s49
inlet-
temp
f9
outlet-
temp
f4
average-tube-temp-subcool
s133
cond-type
r9-
r17
tube-side-fluid
c5
c6
outlet-temp
f4
condensing-temp
c22
avg-subcool-ht-tr-coeff
s51
s52
s53
prnl
alfv
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reliquid-subcool
s130
s131
reu
s50
value1
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c32
F
prnl
alfv
4
cond-type
r9-
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tube-area-
per-pass
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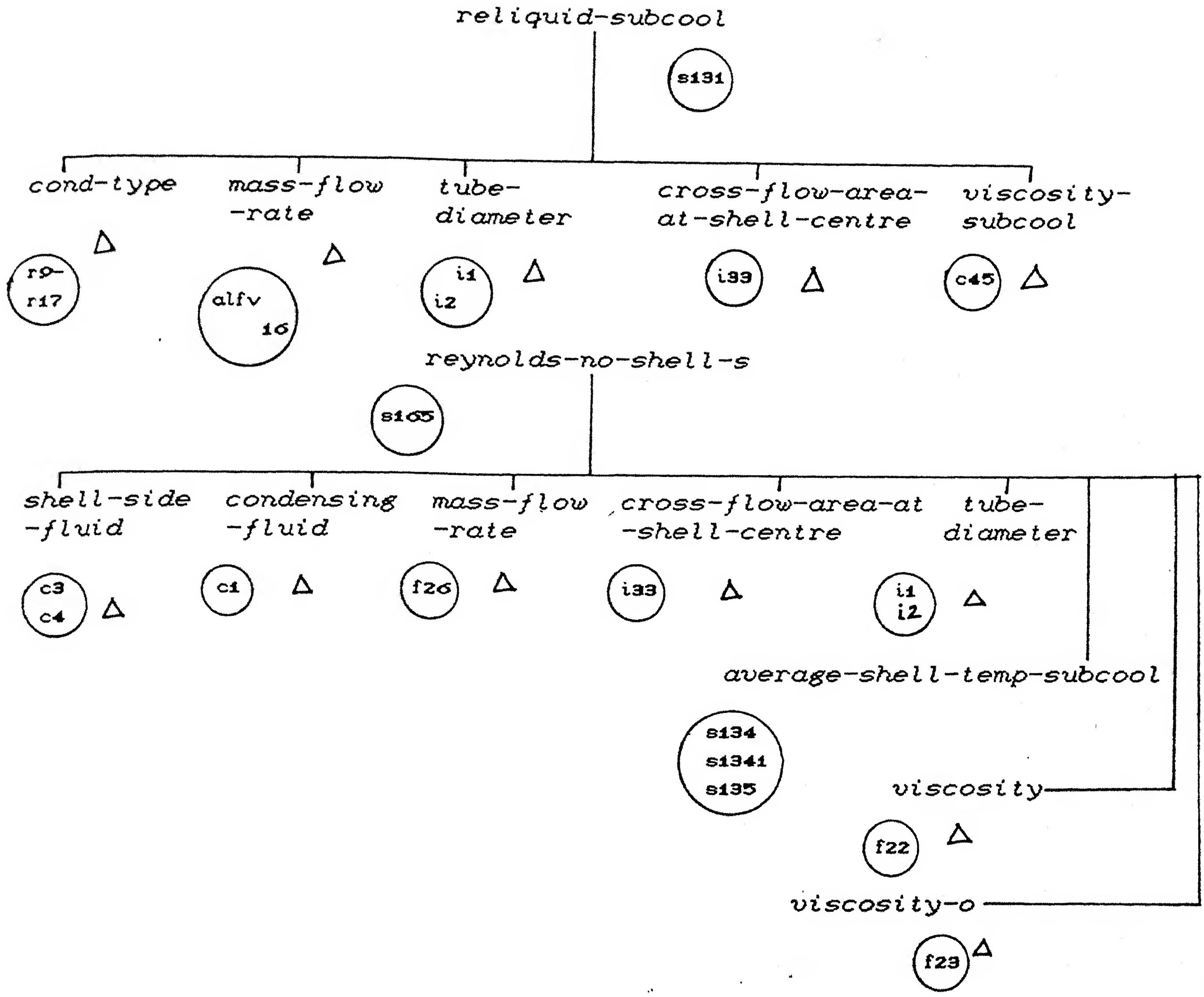
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alfv
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i2
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at-shell-centre
i33
viscosity-
subcool
c45
reynolds-no-shell-s
s165
shell-side
-fluid
c3
c4
condensing
-fluid
c1
mass-flow
-rate
f26
cross-flow-area-at
-shell-centre
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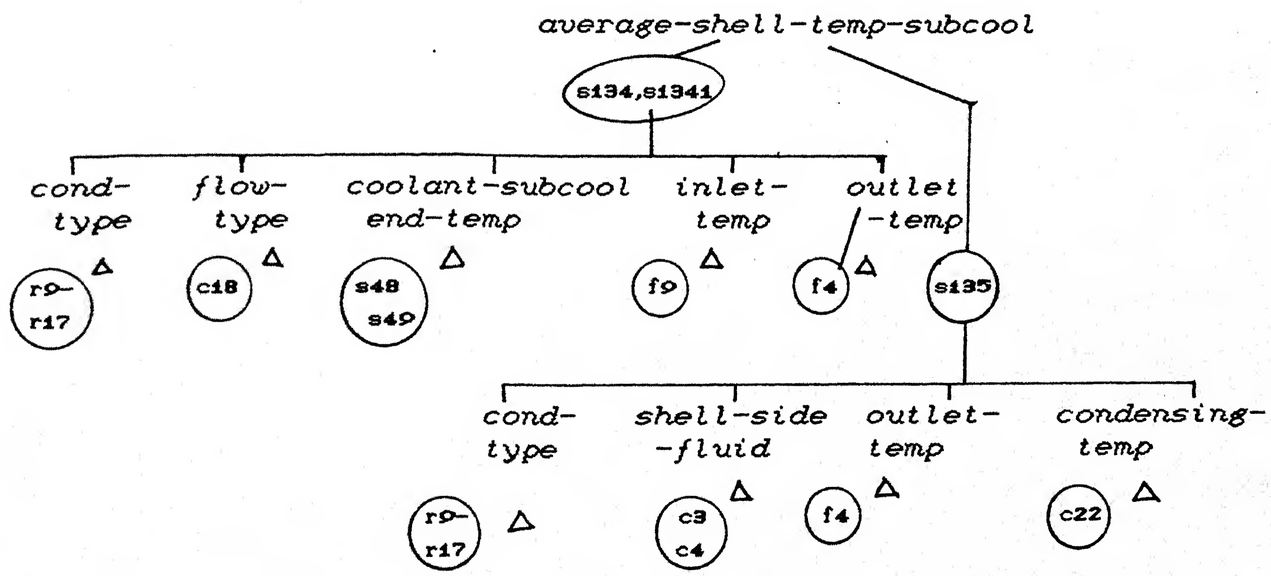
f22
viscosity-o
f23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r17
flow-
type
c18
coolant-subcool
end-temp
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s49
inlet-
temp
f9
outlet
-temp
f4
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cond-
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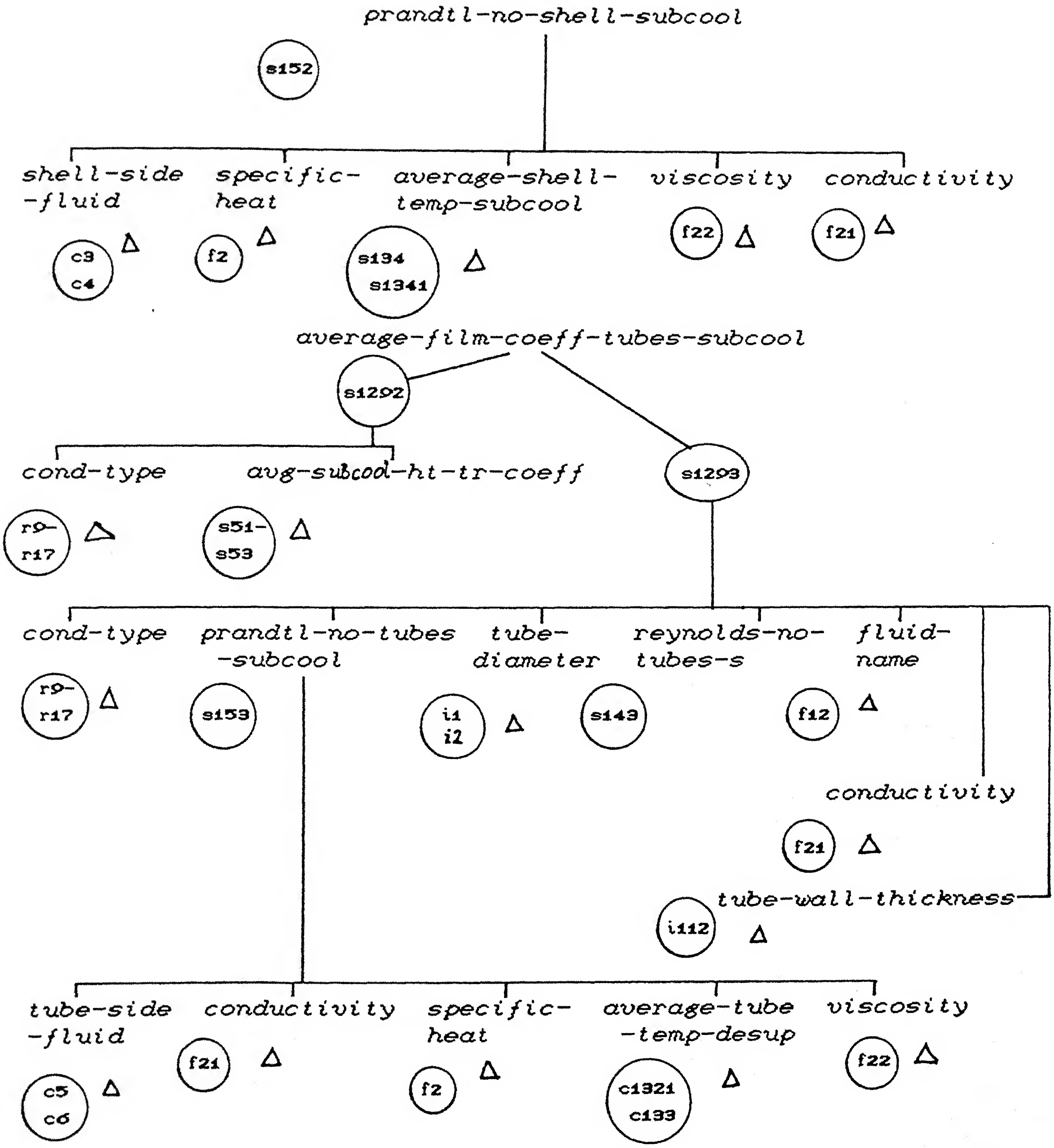
r17
shell-side
-fluid
c3
c4
outlet-
temp
f4
condensing-
temp
c22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c4
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heat
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temp-subcool
s134
s1341
viscosity
f22
conductivity
f21
average-film-coeff-tubes-subcool
s1292
cond-type
r9-
r17
avg-subcool-ht-tr-coeff
s51-
s53
s1293
cond-type
r9-
r17
prandtl-no-tubes
-subcool
s153
tube-
diameter
i1
i2
reynolds-no-
tubes-s
s143
fluid-
name
f12
conductivity
f21
tube-wall-thickness
i112
tube-side
-fluid
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specific-
heat
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average-tube
-temp-desup
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c133
viscosity
f22

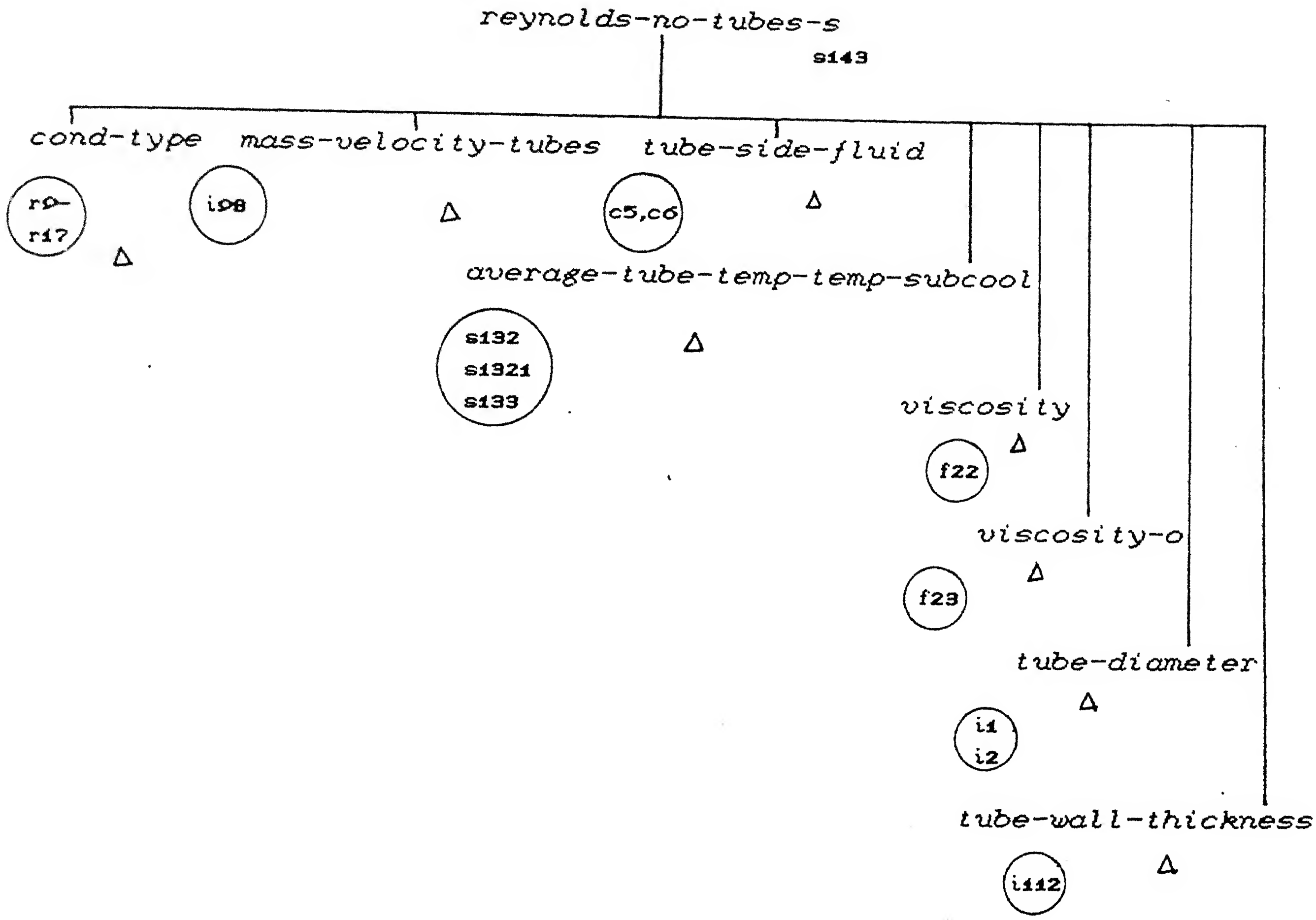

Fig. 5.2 Tree Structure for the Design of Vertical Condensers

6. Now calculate desuperheating area after estimating the overall heat transfer coefficient for desuperheating zone. Area required for the condensation zone should be calculated after estimating the overall heat transfer coefficient for condensation for each step (stepwise method). Area required for subcooling zone is calculated in the similar manner as for the desuperheating zone.

7. Total area required is known from Step 6. Compare this actual required area with the area available for heat transfer. If the comparison is acceptable then one proceeds with further design; else the design should be modified by going back to Step 3.

The rule set for the expert system is, however, developed by using the tree structure for the whole design process. Flow chart is the representation of transfer of control whereas the tree structure is the structure of subproblems generated in trying to achieve the goal.

5.2 Tree Structure for the Design :

The full tree structure for the present expert system is shown in Fig. 5.2 . Each goal (query) may give rise to several subgoals (subqueries). These subqueries are to be satisfied from left to right in the tree-structure. Each query or subquery corresponds to a predicate name in the program. For each predicate the rules present in the expert system have been indicated through their names in the elliptical boxes below each subquery or query. In tree structure, below each predicate three symbols appear : letter Q, letter F and Δ . The Q signifies a question-rule which causes the system to issue a question for user response. The F indicates that the fact exists for the predicate in

consideration.The presence of Δ signifies that the value of this predicate is already known and stored or the tree structure for this predicate is already described somewhere else in Fig. 5.2. To save the space, many times two or more rules for a predicate have been given in one tree diagram if the logic for them is the same.

The tree structure shown in Fig.5.2 is a static template in which each rule and fact is shown only once. The actual tree of goals that will be generated during a computation will be dynamic; several instances of the same rule may occur in this tree, and the tree itself will vary from session to session depending on the user's responses. However, the sequence of steps that it will perform will be the same as that shown in the flow chart of Fig. 5.1.

Let us examine the initial part of the tree structure in detail :

The top-level goal is 'complete', for which two rules c159 and c160 exist. The selection of one of these rules depend upon the value of predicate 'select-condenser'(whether vertical-upflow or vertical-downflow). From top-level query in c159, following sub-queries are generated:

-select-condenser

-cond-type

-tube-diameter

-flooding-mass-velocity

-mass-velocity-tubes

-ask-user

-area-req.

However, if the rule c159 fails at the select condenser, the rule c160 is tried and the new goal 'area-req' is generated.

Consider the rule c159, here the current goal is 'select-condenser' which has rules c8 to c11. It generates three further subqueries :

-cond-type

-t-or-p-condenser

-ask-user

For cond-type 8 rules (r9 to r17) exist and they are tried in the order in which they appear in data base. Rule r9-r10 generates two subqueries 'pressure' (r1) and 'retract-all'. r1 being a question-rule, it issues a question to user and depending on user's response it either succeeds or fails if 'pressure' succeeds, 'retract-all' predicate causes all other rules for 'cond-type' to be unusuable in any further reference and the fact for 'cond-type' is the only thing which is accessible for later use. Rules r11-r17 are self-explanatory on similar lines.

't-or-p-condenser' has again got a question rule and its third predicate is ask-user which causes issuing of question regarding type of condenser. Thus 'select-condenser' goal is made true if every thing goes in a proper way.

The second subquery in rule c159 is 'cond-type' which has already been made true while satisfying the goal 'select-condenser'. The next generated subgoal 'tube diameter' has got one question rule i1 and one fact i2. If the rule i1 fails then the 'tube-diameter' is satisfied from the fact i2. The other remaining subgoals are self-explanatory. The last subquery in rule (c159) is 'area-req' which has three subgoals:
'area-req-condensing', 'area-desup' and 'area-subcool'.

The 'area-req-condensing' generates a new goal 'step-inlet-temp-area-upto-step', which makes use of recursion in

getting a true value. There are three rules c75, c76 and c77 for this predicate. The rule c75 is the boundary condition which causes recursion to end. The rule c75 generates a goal 'coolant-temperature-at-the-start-of-condensation' for which two rules c79 and c8Ø are present.

The rules c76 and c77 follow the same logic and the choice in them is made based upon the new subquery 'flow-type. The <u>other</u> subqueries are :

-dely

-step-inlet-temp-area-upto-step (causes recursion)

-heat-load-per-step

-fluid-name

-mass-flow-rate-cold

-specific-heat

-overall-htc-condensing

-condensing-temp

-log-mtd

And thus the tree for the top goal 'complete' keeps on growing and it can be understood based on the features explained till now.

5.3 <u>Structuring of the Knowledge Base</u> :

5.3.1 Type of Data Structure :

The structure of the rules to a great extent depends upon the type of data structure used. For example, consider the fluid properties (property-1, property-2....etc) for the fluids fluid-1 and fluid-2. Now there can be various types of data structure :

```
        (fluid-1        property-1       <val>)
(I)
        (fluid-2        property-2       <val>)

        (property-1     fluid-1          <val>)
(II)    (property-1     fluid-2          <val>)
        (property-2     fluid-1          <val>)

        (fluid-1   property-1...property-n  <val 1>...<val n>)
(III)
        (fluid-2   property-1...property-n  <val 1>...<val n>)

        (property-1-and-2  fluid-1    <val 1>    <val 2>)
(IV)
        (property-1-and-2  fluid-2    <val 1>    <val 2>)

        (property-1-of-fluid-1       <val 11>)
(V)     (property-1-of-fluid-2       <val 12>)
        (property-2-of-fluid-1       <val 21>)
```

and so on.

Let us consider the types (I) and (II). Type I is centered around fluids (fluid-1, fluid-2 etc) while type-II is centered around the properties (density, temperature etc here written as property-1, property -2 etc). Since the number of fluids is small in our case, viz., 2, we get just two predicates and so the number of explanations, questions to be provided etc gets reduced in number where as type II providing a large number of predicates gives flexibility of association of different questions, explanations etc with each one of them. The problem of type I exists also in type III though it saves space.

It is important to understand that there has to be a practical limit beyond which additional flexibility becomes a burden rather than a help. For example, in type V, the

explanation for (say) density would have to be repeated over and over again. Wherever the same explanation is sufficient for several things, they can be combined in one predicate as for example in type IV.

The type IV is useful when the fluid is undergoing phase change and we need the properties of both the phases. Then the <val 1> can be property of liquid phase and <val 2> of vapour phase. In the present expert system both type II and type IV have been used.

5.3.2 Different Predicates Used :

The computational predicates take their arguments and return true (T) or false (Nil) according to the condition e.g.. <, >,le, ge etc. (le = less than or equal to and ge = greater than or equal to). Most of the predicates defined for this system take one argument which is a numerical value e.g. heat-rate, no-of-tubes, shell-diameter. Such predicates essentially have a rule, and most of the time they are inferred from a rule.

Other types of predicates are those which have more than one argument. The need for defining such predicates arises because of change in references and requirement of storing many properties, e.g. :

(specific-heat fluid-1 <temp-val> <val 1>)

(specific-heat fluid-2 <temp-val> <val 2>)

The built-in predicates in VIDHI like 'ask-user' and 'retract-all' have their own significance and have been explained earlier.

5.3.3 Types of Rules :

The rules used here are mostly of the type which makes use of an expression for assigning value to a variable argument of the predicate :

A rule of the form

```
(defasrt s119 (subcool-ht-load  ?qs) <-
  (mass-flow-rate condensation-side ?mh)
  (fluid-name hot-fluid ?name-h)
  (outlet-temp   ?name-h   ?tho)
  (condensing-temp  ?name-h  ?tsat)
  (specific-heat  ?name-h ?cpl  ?cpg)
  (= ?qs (product ?mh  ?cpl  (diff  ?tsat  ?tho))))
```

is equivalent to the expression

$$q_{sub} = \dot{m}_h \times c_{pl} \times (T_{ho} - T_{sat})$$

This can be asserted as a logic expression in other rules as follows:

```
(defasrt S63 (area-subcool ?acool) <-
  (subcool-ht-load ?qs)
  (overall-htc-subcool ?uo)
  (= ?acool (quotient ?qs (product ?uo...))))
```

The second type of rule is one which takes purely logical decisions, consider the rule:

```
(defasrt c3 (shell-side-fluid ?name-s) <-
  (cond type shell-side-condensation)
  (condensing-fluid ?name-s)
  (retract-all shell-side-fluid))
(defasrt c4 (shell-side-fluid ?name-s)<-
  (cond-type tube-side-condensation)
```

```
(fluid-name cold-fluid ?name-s)
(retract-all shell-side-fluid))
```

The first rule says that if shell-side-condensation is going on then the condensing-fluid is the shell-side-fluid and the second rule says that if it is case of tube-side-condensation then the cold-fluid (i.e. non-condensing fluid) is the shell-side-fluid.

It is to be noted that in the first type of rules the ordering of subqueries in antecedent is important,because all the variables used in a computational functions or predicates should have bindings by the previous subqueries.

5.4 Encoding a New Rule :

Let us consider a brief example illustrating how the available knowledge is converted into a rule. Consider the following knowledge available about pitch-layout :

1. The most commonly used pitch-layout is the staggered-30.
2. If the restriction on shell-side pressure-drop is strict, then inline-90 is the suitable type.
3. If the requirement of mechanical cleaning is frequent then staggered-45 is the most suitable type.

The first step is to arrange these statements in the order of importance.

Along with this, the important parameters are selected as predicates. So we have :

Order of Importance	Serial-number	Predicates
1	2	(pressure-drop-strict)
2	3	(mechanical-cleaning-frequent)
3	1	

For the type of pitch-layout we can have predicate 'pitch-layout'.

Now using the VIDHI syntax, rules for 'pitch-layout' can be written as follows :

```
(defasrt f44 (mechanical-cleaning-frequent) <-
  (ask-user (source) (target)
  (question  Is  the  requirement  of  shell  side
 mechanical-cleaning-frequent)))

(defasrt f 45 (pressure-drop-strict) <-
  (ask-user (source) (target)
  (question Is the limitation on shell side pressure-drop
   strict)))
(defasrt f46 (pitch-layout ?x) <-
  (pressure-drop-strict)
  (= ?x inline-9Ø)
  (rertract-all pitch-layout))
(defasrt f47 (pitch-layout ?x) <-
  (mechanical-cleaning-frequent)
  (= ?x staggered-45)
  (retract-all pitch-layout))
(defasrt f48 (pitch-layout ?x)<-
  (= ?x staggered -3Ø))
```

It can be noted that the rules f46 and f47 cannot be interchanged since if the user wants to satisfy the requirements of both the predicates (pressure-drop-strict) and (mechanical-cleaning-frequent), then we want f46 to get control rather than f47.

6. RESULTS AND DISCUSSION

6.1 How to Use the System :

If the decision regarding the use of shell-and-tube condenser having an E-type shell has been taken, the present system can be used to design it. The system is very interactive and user friendly. It issues the questions to the user at every step giving sufficient help wherever possible.

The questions asked by the system are of two types :
a. Mandatory Questions and b. Optional Questions

Mandatory questions collect that vital information from the user without which nobody can even think of designing a condenser. If the user responds incorrectly to this information or, is not able to provide it, the system can't proceed to design the condenser. The mandatory information needed has been listed in Table 6.1 and must be collected before proceeding to execution.

Optional questions are not so critical and even if user responds to these questions saying "dontknow", still the design can proceed. These optional questions are issued to the user to enable him getting a tailor-made design according to his need. For example, user may prefer only one particular shell-diameter or may have an upper limit on its value; in that case he should specify it. Also, if the user before hand has some information regarding design, (in the second iteration he definitely has some) e.g., number of tubes, number of baffles, etc., he should specify it. This will save unnecessary time used in computing these

TABLE 6.1

Mandatory Questions

Question		Condensing fluid	Coolant
Name of the fluid			
Specific heat	J/kg-K	<value-liquid><value-gas>	<value>
Thermal conductivity	W/m-K	<value-liquid><value-gas>	<value>
Thermal conductivity of tube material	W/m-K		
Inlet temperature	$^{\circ}C$	<value>	<value>
Outlet temperature	$^{\circ}C$	<value>	<value>
Condensing temperature	$^{\circ}C$	<value>	<value>
Mass flow rate	kg/s	<value>	<value>
Absolute viscosity at average temperature (Liquids only)	cP		<value>
Absolute viscosity at some other temperature	cP		<value>
Absolute viscosity at condensing temperature	cP	<value-liquid><value-gas>	
Density	kg/m^3	<value-liquid><value-gas>	
Condensing pressure	kPa	<value>	
Enthalpy of vaporization	J/kg	<value>	
Approximate overall heat-transfer coefficient	W/m^2-$^{\circ}C$		
Viscosity of condensate	cP		
Aspect ratio			
Flow-direction			

TABLE 6.2

Optional Questions

Question		
Shell diameter	mm	<value>/dontknow
Tube diameter	mm	<value>/dontknow
Area of heat transfer	m^2	<value>/dontknow
Number of baffles		<value>/dontknow

6.2 Sample Sessions :

Two sample sessions are presented in the Appendix to illustrate the behaviour of expert system under different type of responses provided by the user.

Session 1 illustrates the case where a mandatory question is not answered. The system is not able to proceed beyond that point.

Session 2 illustrates the normal behaviour of the system as expected. The user answers the questions in a proper way after seeking the explanations whenever he is in doubt.

6.3 Limitations of the Present System and Scope for Future Work

The limitations of the present system are because of two reasons. One set of limitations exist because the VIDHI itself is undergoing development, which of course requires further work on the part of a Computer Scientist. The other set of limitations is due to insufficient knowledge base which still requires additional data and literature survey. These can be summarised as follows :

a. The rules for the calculation of pressure drop in two-phase zone are not included. So the pressure rating of the design is not a part of this thesis.

b. Present work considers only the case of single shell-pass and single tube-pass condensers. For the case of multi tube-pass, the step-wise method in two-phase zone will have to be modified considerably and becomes very complicated. However, using an average condensation coefficient, this extension can be easily incorporated.

c. The present system is only for E-type shell.

d. The present system lacks the provision of changing an already given value of a particular design parameter. This arises because of inability of declaring data dependencies in the 'Shell' and absence of such provision in the tree structure.

All the above limitations provide the scope for future work.

6.4 Conclusions :

The expert system developed here makes use of the 'Shell - VIDHI' (Sangal,1988). It is based on logic programming and is highly interactive. It is capable of designing a vertical condenser from heat transfer point of view. The rules involving the shell side computations make use of 'Bell-Delaware Method' in the rating program. In the condensation zone, the stepwise or successive summation method is used to take into account the variation in condensation coefficient due to the change in vapour fraction of the mixture. After the rules for the two-phase pressure drop calculations are added, the system will be able to completely design a single tube, single shell pass vertical condenser using E-type of shell from the thermal performance point of view.

Additional rules can be easily added to include other types of multipass shell-and-tube condensers. After some field testing, the system can be put into commercial use. Thus, the present work marks only a beginning towards this ultimate goal.

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APPENDIX

SAMPLE SESSION 1

```
% ~sangal/vidhi.exe

14.load cini
[load cini]
[load comp]
[load list]
[load list1]
[load cond]
[load alv1]
[load cnds1]
[load cnds2]
[load cnds3]
[load cnds4]
[load cnds5]
[load cnds6]
[load itercond]
[load fixedcond]
[load vidhiupdate.l]
t
15.design
("what is the pressure of condensing vapour :
   high,very-low,or intermediate")intermediate
("Is the vapour very-corrosive,corrosive,or non-corrosive")corrosive
(is the condensation total or partial)total
("We have a case of" tube-side-condensation "
*Now please  select one of the types after
  studying the following table$
  -------------------------------------------------------------------$
```

	horizontal		vertical-downflow		vertical-upflow	
single-component vapour	g	av	g	av	f	b
multi-component vapour	f	b	g	b	f	c
subcooled-condensate	p	x	g	av	x	x
pressure-drop						
high	g	b	g	c	x	c
low	p	b	f	c	g	c
coolant						
liquid	g		g		g	
gas	g		g		g	
boiling	g		g		g	

```
acceptability: g=good ,  p=poor , x= not acceptable or not recommended
               f=fair
```

predictability: av=average ~ 25%
b =fair ~<50%
c =poor ~>50%
x =no method or not recommended

horizontal condensers have possibility of slugging.
vertical downflow handles dirty or polymerizing vapours.
please answer on right hand side")vertical-upflow
(Give the value of the tube outside diameter in mm)what

(the recomended tube dimensions are :-

tube o.d mm	wall thickness mm	tube i.d mm	outside surface sq m / m
6.0	0.5	5.0	0.019
8.0	1.5	5.0	0.025
10.0	1.5	7.0	0.031
14.0	2.0	10.0	0.044
18.0	2.0	14.0	0.057
20.0	2.0	16.0	0.063
25.0	2.5	20.0	0.079
30.0	2.5	25.0	0.094
38.0	2.5	33.0	0.119
44.5	2.5	39.5	0.139
51.0	2.5	46.0	0.160

select a suitable tube diameter or tube wall thickness from the above table . generally, tubes below 20.0 mm o.d are not recommended since they have a large pressure drop. smaller diameter tubes give larger heat transfer area for the same shell diameter.
you may say dontknow also.)>38.0
(what is the name of condensing fluid)steam
("what is the condensing temperature of" steam "
in degree celsius at condensing pressure")what

(This is a mandatory question)>100.0
("Give the absolute viscosity of liquid and vapour
phase respectively of" steam "in centipoise at
temperature" 100.0 deg celsius)0.278 0.0126
("please specify the liquid and vapour phase density
of" steam at temperature 100.0 in kg/m3)958.3 0.597
("what is the value of surface-tension coefficient
for liquid-condensate in mN/m,or,dyne/cm")58.0
(what is the taper of tube-end in degrees from horizontal)60.0
(Give the value of the tube-wall-thickness in mm)what

(the recomended tube dimensions are :-

tube o.d mm	wall thickness mm	tube i.d mm	outside surface sq m / m
6.0	0.5	5.0	0.019
8.0	1.5	5.0	0.025
10.0	1.5	7.0	0.031
14.0	2.0	10.0	0.044
18.0	2.0	14.0	0.057
20.0	2.0	16.0	0.063
25.0	2.5	20.0	0.079
30.0	2.5	25.0	0.094
38.0	2.5	33.0	0.119
44.5	2.5	39.5	0.139
51.0	2.5	46.0	0.160

select a suitable tube diameter or tube wall thickness from the above table . generally, tubes below 20.0 mm o.d are not recommended since ~~they have a large pressure drop. smaller diameter tubes give larger~~ heat transfer area for the same shell diameter.
you may say dontknow also.))2.5
(What is the name of the cold-fluid)water
(what is the mass-flow-rate of the condensing fluid in kg/s)3.5
(Give the value of the shell diameter in mm)dontknow
(Give the area of heat transfer in sq m)what

(if this the first round of calculations or
if you know the value of overall heat transfer coefficient in
W/ sq m K, say 'dontknow' else give the value from the
initial round of calculation))ontknow
("Give the value of overall heat transfer coefficient in
W/sq-m-K from previous experience or from
explanation available")dontknow
(what is the taper of tube-end in degrees from horizontal)60.0
("what is the flow-directions of the streams:
co-current, counter")counter
("How many number of steps should be choosen to
determine required condensing area by step-wise method")4
(" what is the value of enthalpy of vaporization
of condensing fluid in J/kg")2256700.0
("please specify the specific heats of liquid and vapour
phase respectively of" steam in j/kg-K)4220.0 2030.0
(Please specify the inlet-temp of steam in deg-celsius)110.0
(Please specify the outlet-temperature of steam in deg celsius)90.0
(Please specify the inlet-temp of water in deg-celsius)32.0
(Please specify the outlet-temperature of water in deg celsius)40.0
(please specify the specific-heat of water in j/kg k)4178.5
(please specify the conductivity of tube material in W/m- K)38.0

```
this is a table for comparision of the results
---------------------------------------------------------------
the heat transfer area required sq m = ($var areq)
the actual heat transfer area available sq m = ($var a-o)
the desuperheating area required sq m = ($var a-desup)
the condensation area required sq m = ($var acon)
the subcooling area required sq m = ($var acool)
shell side fluid = ($var name-s)
tube side fluid = steam
no of baffles = ($var n-b)
no of tubes = ($var n-t)
tube side passes = 1
shell side passes = ($var ns)

----------------------------------------------------------
the different correction-factors for heat transfer are
----------------------------------------------------------
window correction factor      = ($var j-c)
baffle leakage correction factor    = ($var j-l)
bundle bypass correction factor     = ($var j-b)
adverse temperature gradient correction factor      = ($var j-r)
total correction factor     = Error: Non-number to add ($var j-c)
<1>: (reset)

16.exit
%
```

NOTE: Here the User did not specify either Approximate Area or approximate Overall Heat Transfer Coefficient, so the Design could not be completed.

```
% ~sangal/vidhi.exe

14.load cini
[load cini]
[load comp]
[load list]
[load list1]
[load cond]
[load alv1]
[load cnds1]
[load cnds2]
[load cnds3]
[load cnds4]
[load cnds5]
[load cnds6]
[load itercond]
[load fixedcond]
[load vidhiupdate.l]
t
15.design
("what is the pressure of condensing vapour :
   high,very-low,or intermediate")intermediate
("Is the vapour very-corrosive,corrosive,or non-corrosive")corrosive
(is the condensation total or partial)total
("We have a case of" tube-side-condensation "
*Now please  select one of the types after
  studying the following table$
  -------------------------------------------------------------------$
```

	horizontal		vertical-downflow		vertical-upflow	
single-component vapour	g	av	g	av	f	b
multi-component vapour	f	b	g	b	f	c
subcooled-condensate	p	x	g	av	x	x
pressure-drop						
high	g	b	g	c	x	c
low	p	b	f	c	g	c
coolant						
liquid	g		g		g	
gas	g		g		g	
boiling	g		g		g	

```
acceptability: g=good ,  p=poor , x= not acceptable or not recommended
               f=fair

predictability: av=average ~ 25%
                b =fair    ~<50%
                c =poor    ~>50%
                x =no method or not recommended

 horizontal condensers have possibility of slugging.
 vertical downflow handles dirty or polymerizing vapours.
 please answer on right hand side")vertical-downflow
("what is the flow-directions of the streams:
   co-current, counter")what

(Of course the system is developed for cross
-flow E-type of shells,so if the both fluids enter on the same-side
it is a case of co-current, else counter.
This is a mandatory question)>counter
("How many number of steps should be choosen to
   determine required condensing area by step-wise method")4
(what is the name of condensing fluid)what

(this is a mandatory question)>steam
(what is the mass-flow-rate of the condensing fluid in kg/s)3.5
(" what is the value of enthalpy of vaporization
   of condensing fluid in J/kg")2256700.0
(What is the name of the cold-fluid)water
("please specify the specific heats of liquid and vapour
                phase respectively of" steam in j/kg-K)4220.0 2030.0
(Please specify the inlet-temp of steam in deg-celsius)110.0
(Please specify the outlet-temperature of steam in deg celsius)90.0
("what is the condensing temperature of" steam "
    in degree celsius at condensing pressure")100.0
(Please specify the inlet-temp of water in deg-celsius)32.0
(Please specify the outlet-temperature of water in deg celsius)40.0
(please specify the specific-heat of water in j/kg k)4178.5
(please specify the conductivity of tube material in W/m- K)38.0
(Give the value of the shell diameter in mm)what

( if there is a restriction on
 the shell-diameter give the value else say
 dontknow)>dontknow
(Give the area of heat transfer in sq m)what

(if this the first round of calculations  or
 if you know the value of overall heat transfer coefficient in
 W/ sq m K, say 'dontknow' else give the value from the
 initial round of calculation )>dontknow
("Give the value of overall heat transfer coefficient in
      W/sq-m-K from previous experience or from
      explanation available")what

(some typical ranges are given in
 the following table--
```

vapour	coolant	U,W/sq-m-K
alcohol	water	50-1100
dowtherm	tall oil	40-450
dowtherm	dowtherm	450-680
high-bioling-hydrocarbons		
under vacuum	water	100-280
low-bioling-hydrocarbons	water	450-1140
organic solvents	water	550-1140
hydrocarbons	oil	140-230
kerosene	water	170-370
kerosene	oil	110-170
naphtha	water	280-430
naphtha	oil	110-170
steam	feed water	1800-5700
vegetable-oils	water	110-280
organic steam,azeotrope	water	220-450
air-coolers		
steam	air	730-800
~~ammonia~~	~~air~~	~~550-680~~
light-hydrocarbon	air	450-540
light-naphtha	air	400-450
freons	air	340-450
heavy-naphtha	air	340-400

please answer on right hand side
This is a mandatory question)>1800.0
(Is the limitation on shell side pressure-drop-strict)n
(Is the requirement of shell side mechanical-cleaning-frequent)n
(Give the value of the tube outside diameter in mm)what

(the recomended tube dimensions are :-

tube o.d mm	wall thickness mm	tube i.d mm	outside surface sq m / m
6.0	0.5	5.0	0.019
8.0	1.5	5.0	0.025
10.0	1.5	7.0	0.031
14.0	2.0	10.0	0.044
18.0	2.0	14.0	0.057
20.0	2.0	16.0	0.063
25.0	2.5	20.0	0.079
30.0	2.5	25.0	0.094
38.0	2.5	33.0	0.119
44.5	2.5	39.5	0.139
51.0	2.5	46.0	0.160

```
 select a suitable tube diameter or tube wall thickness from the above
 table . generally, tubes below 20.0 mm o.d are not recommended since
 they have a large pressure drop. smaller diameter tubes give larger
 heat transfer area for the same shell diameter.
 you may say dontknow also. )>38.0
(Give the value of the aspect ratio)12.0
(Is the steam fouling)n
(Give the inlet-pressure of the steam in kpa)101.3
(Is a slightly-greater-diameter of the shell tolerable)y
(Give the inlet-pressure of the water in kpa)101.3
(Give the number of baffles)what

( the no of baffles decide the shell side
 reynolds number, lower value gives a lower Reynolds Number
 and lower pressure drop.
 if the value of baffle leakage correction factor is less than
 0.7 reduce the number of baffles. This increases the cross flow
 area at shell centre and hence the correction factor. )>dontknow
("Give the absolute viscosity of" water "
at" 36.0 deg celsius in cP)0.710
(Give the thermal conductivity of the water in W / m K)0.626
(please classify the water "in any of the
    following categories :-
    (1)light-liquid                       light
    (2)medium-liquid                      medium
    (3)heavy-hot-liquid                   heavy-hot
    (4)heavy-cold-liquid                  heavy-cold
    (5)very-heavy-hot-liquid              very-heavy-hot
    (6)very-heavy-cold-liquid             very-heavy-cold
    (7)gas-at-a-pressure < 200 kpa        gas-200
    (8)gas-at-a-pressure < 1000 kpa       gas-103
    (9)gas-at-a-pressure < 10000 kpa      gas-104

the gas-pressure is the absolute pressure
the liquid has to be classified on the basis of viscosity
 answer by typing the word on right hand side; this is a
 mandatory question")light
("Give the absolute viscosity of the" water "at some other
  temperature. Give the temperature in deg celsius followed
  by the viscosity in cP.")95.0 0.299
(Give the value of the tube-wall-thickness in mm)2.5
("Give the absolute viscosity of liquid and vapour
    phase respectively of" steam "in centipoise at
    temperature" 100.0 deg celsius)0.278 0.0126
("please specify the conductivity of liquid and
    vapour phase respectively
   of" steam in W/m-K)0.679 0.025
("please specify the liquid and vapour phase density
   of" steam at temperature 100.0 in kg/m3)958.3 0.597
```

```
(please classify the steam "in any of the
    following categories :-
    (1)light-liquid                        light
    (2)medium-liquid                       medium
    (3)heavy-hot-liquid                    heavy-hot
    (4)heavy-cold-liquid                   heavy-cold
    (5)very-heavy-hot-liquid               very-heavy-hot
    (6)very-heavy-cold-liquid              very-heavy-cold
    (7)gas-at-a-pressure < 200 kpa         gas-200
    (8)gas-at-a-pressure < 1000 kpa        gas-103
    (9)gas-at-a-pressure < 10000 kpa       gas-104

the gas-pressure is the absolute pressure
the liquid has to be classified on the basis of viscosity
 answer by typing the word on right hand side; this is a
 mandatory question")gas-200
("please classify the condensed fluid in any one
    of the following categories:-$
  (1) light-liquid                          light
  (2) medium-liquid                         medium
  (3) heavy-hot-liquid                      heavy-hot
  (4) heavy-cold-liquid                     heavy-cold
  (5) very-heavy-hot-liquid                 very-heavy-hot
  (6) very-heavy-cold-liquid                very-heavy-cold

  condensed liquid has to be classified on the basis of
  viscosity ,  answer on right hand side")light
("what is the value of viscosity of condensate(liquid)
    in centipoise at temperature" 95.0 deg celsius)0.299
("please classify the vapour in any one of the following
   categories:-$
   [1] vapour at a pressure < 200 kpa      gas-200
   [2] vapour at a pressure < 1000 kpa     gas-103
   [3] vapour at a pressure < 10000 kpa    gas-104
  the gas pressure is absolute pressure
   answer on right hand side")gas-200
("what is the value of viscosity of condensing vapour
   in centipoise at temperature" 105.0)0.0125


yes
Should I try for another answer(y/n):n
 ------------------------------------------------------------
 this is a table for comparision of the results
 ------------------------------------------------------------
 the heat transfer area required sq m = 68.74666349468933
 the actual heat transfer area available sq m = 70.6693321090584
 the desuperheating area required sq m = 5.345516950502597
 the condensation area required sq m = 61.86690341596033
 the subcooling area required sq m = 1.534243128226397
 shell side fluid = water
 tube side fluid = steam
 no of baffles = 10
 no of tubes = 63
 tube side passes = 1
 shell side passes = 1
```

```
---------------------------------------------------------------------------
the different correction-factors for heat transfer are
---------------------------------------------------------------------------
window correction factor        = 0.8285758053028381
baffle leakage correction factor    = 0.9216461040296201
bundle bypass correction factor     = 0.5781721566837544
adverse temperature gradient correction factor     = 1.0
total correction factor     = 0.4415232852097603

---------------------------------------------------------------------------
the shell side parameters are
---------------------------------------------------------------------------
fluid name = water
shell diameter mm = 495.0370839406971
length of the shell mm = 5940.445007288366
no of baffles = 10
central baffle spacing mm = 531.0397818546335
percentage of baffle cut = 36.36363639772728
centriangle of baffle cut deg = 148.3576872464027
upper centriangle of baffle cut  deg = 144.0145676229977
bundle to shell inside diameter clearence mm = 96.08870522807266
aspect ratio = 12.0
cross flow area at the shell centreline sq mm = 93398.41706357225
fraction no of tubes in one window = 0.3064751325185172
fraction no of tubes in pure cross flow = 0.3870497349629656
bundle to shell bypass area sq mm = 40937.16920777183
shell to baffle leakage area sq mm = 2322.487039472815
tube to baffle hole leakage area sq mm = 2108.091156967368
shell to baffle clearence mm = 5.080148235762788
no of sealing strip pairs = 0
no of shell side passes = 1

---------------------------------------------------------------------------
the tube side parameters are
---------------------------------------------------------------------------
name of the fluid = steam
tube diameter  mm  = 38.0
tube wall thickness mm = 2.5
tube length mm = 5841.437600400968
no of tubes = 63
no of tube side passes = 1
tube bundle type = pull-through-floating-type
nil
16.exit
%
```